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CentER

Essays on Incentives in Regulation and Innovation

Jos Jansen

Essays on Incentives

in

Regulation and Innovation

Essays on Incentives

in

Regulation and Innovation

PROEFSCHRIFT

ter verkrijging van de graad van doctor aan de Katholieke Universiteit Brabant, op gezag van de rector magnificus, Prof. dr. F.A. van der Duyn Schouten, in het openbaar te verdedigen ten overstaan van een door het college voor promoties aangewezen commissie in de aula van de Universiteit op

maandag 24 januari 2000 om 14.15 uur

door

JOHANNES ANTONIUS JANSEN
geboren op 31 maart 1969 te Renkum

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PROMOTORES: Prof. dr. P. Bolton
Prof. dr. E.E.C. van Damme

…"And what there is to conquer
By strength and submission, has already been discovered
Once or twice, or several times, by men whom one cannot hope
To emulate — but there is no competition —
There is only the fight to recover what has been lost
And found and lost again: and now, under conditions
That seem unpropitious. But perhaps neither gain nor loss.
For us, there is only the trying. The rest is not our business."

[T.S. Eliot *East Coker* V]

Preface

During the years that I worked on this thesis I had the good fortune to interact with many interesting people. In this preface I would like to acknowledge their role in my work.

At August 1994 I became a PhD student at CentER. The excellent research atmosphere at CentER has been of invaluable help to me during my PhD studies. The interesting courses that I followed in CentER's graduate school and the NAKE network, numerous seminars, opportunities to travel, and the interaction with faculty, students and visitors helped me to become a better researcher. I am most grateful to CentER for offering me these opportunities. Eric van Damme supervised my work since the early days of my PhD studies. My extensive discussions with him taught me how to think critically about economic problems. Eric's advice and support were, and still are, of great help to me. Thank you, Eric! Besides sharpening my theory skills, Eric involved me in two of his consulting projects. I am grateful to him for giving me such a unique opportunity to get a flavor of economic policy in practice.

In the early Spring of 1996 I met Patrick Bolton. My work benefited greatly from my discussions with him. These discussions are still a source of inspiration to me. I am not only deeply indebted for Patrick's constructive comments and advice, but also for his invitation and arrangement of my visit to the Economics Department of Princeton University. My two months in Princeton, with its excellent faculty, staff and seminars, were an intense and memorable experience. Naturally, I would like to acknowledge the hospitality of Princeton's Economics Department.

During my period at CentER I assisted Dolf Talman in teaching his Master's classes. Dolf's enthusiasm and advice helped me to improve my "blackboard skills", for which I am grateful. I would also like to thank Dolf for his detailed comments on an early draft of the thesis. I gratefully acknowledge the fact that Pieter Ruys expressed continuous interest in my work.

From January to October 1997 I could visit GREMAQ in Toulouse through the ENTER PhD exchange network. The Toulousian institute, with its top seminars, faculty and students, provided me with an excellent research atmosphere. The hospitality of GREMAQ is gratefully acknowledged. During this period Bruno Jullien was so kind to supervise me, for which I am very grateful. I am honored by Bruno's willingness to participate in my PhD committee, and I regret that in the end his participation had to be cancelled, due to practicalities. In Toulouse I could participate in Jacques Crémer's discussion group. I am grateful for Jacques' generosity.

The year in which I completed my thesis, I worked as a research fellow at the research unit Competitiveness and Industrial Change (CIC) of the Wissenschaftszentrum Berlin (WZB). Research unit CIC is a stimulating place for research in IO. I enjoyed the interaction with colleagues, the good seminars, and CIC's great facilities, and hope to keep on doing so in the future. I am deeply indebted to Lars-Hendrik Röller for his patience, generosity, and confidence during this final year.

In Rotterdam, during my undergraduate studies, Sanjeev Goyal taught me the basic principles of microeconomics, and triggered my interest in the field. He stimulated me to do a PhD, and has always showed interest in my work. I gratefully acknowledge the stimulating discussions I had with Sanjeev. One of these discussions initiated my thinking for the main body of this thesis (i.e. Part II).

Naturally, I am very grateful to Sanjeev Goyal, Lars-Hendrik Röller, Pieter Ruys, and Dolf Talman for being on my committee.

Many other people contributed to this work through discussions, and by giving comments and suggestions. I would like to thank, among others, Dilip Abreu, Andreas Blume, Aleix Calveras, Martin Dufwenberg, Péter Esö, Guido Friebel, Doh-Shin Jeon, Marco Haan, Dan Kovenock, Wilko Letterie, Eric de Laat, Johan Lagerlöf, Philippe Marcoul, Nicolas Melissas, Pierre Mohnen, Giuseppe Moscarini, Fréderic Pivetta, Alex Possajennikov, Andrea Prat, Thijs ten Raa, Luca Rigotti, Martin Ruckes, Aldo Rustichini, Yossi Spiegel, Konrad Stahl, Johan Stennek, Jean Tirole, Frank Verboven, and Vincent Verouden.

My colleagues in Tilburg, Toulouse and Berlin deserve a big thank-you. Among them are my two office mates, Paul de Bijl and Maria Montero, the co-editors of the GraDUAL, and my two "paranimfs" Erik Canton and Trea Laske. During my PhD studies I received administrative support from many people. I would like to thank Nicole van Boxel, Georgina Broeken, Annemieke Dees, Ingrid Meeder, Josette van Muijden, Kristel Peijs, and Marjoleine de Wit of CentER, Aude Schloesing of GREMAQ, Kathleen Hurley and Christine Alito of Princeton, and Bianca Faber, Olaf Reimann, and Christopher Xitco of the WZB for their kind support.

During my PhD studies I could travel to visit departments, and participate in many conferences and workshops. My participation was made financially possible through the generosity of NWO, EU's Erasmus Program, ENTER, Shell Nederland, TMR project EMSNI, Studienzentrum Gerzensee, CEPR, The Review of Economic Studies, EARIE (Dresdner Bank), Verein für Socialpolitik (BMW), CentER, and WZB. Their financial support is gratefully acknowledged.

Finally I would like to thank my friends and family for sharing good as well as bad times with me. My most special thanks go to Maria Antonietta Carboni for her encouragement and support.

Jos Jansen
Berlin, November 1999

Contents

Chapter 1

General Introduction

1.1 Introduction

This thesis deals with incentive and information problems of strategically interacting firms. Since the seminal contributions of Spence (1973) and Akerlof (1970) the literature on problems of incentives and information has grown steadily. The growth of information economics is reflected in the growth of the number of fields in which its insights are applied. Among these fields are industrial organization, the theory of regulation and procurement, the theory of banking, corporate finance, and public economics. This thesis contributes to the field with the analysis of a problem of optimal incentive regulation, and a problem of information and incentives in innovation. These problems and their solutions are introduced in the remainder of this introductory chapter.

In particular, the next section discusses the problem and contribution of the second chapter. This chapter studies optimal incentive regulation and organization of an industry for complementary inputs. Section 3 of this Introduction discusses the contribution of the thesis's third chapter. These contributions are to the topic of strategic information revelation and revenue sharing in races for an innovation. Section 4 discusses chapter 4, which studies strategic preannouncements and concealments in innovative industries. Finally section 5 summarizes the structure of the thesis.

1.2 Regulating Complementary Inputs

The theory of optimal incentive regulation is relevant for both economic policy and (applied) theory. It gives economic insights on basic regulatory problems, and it contributes to the theory of information economics. In the next subsection we sketch the problem of regulating complementary inputs, while in the second subsection we explain the main results from solving the problem.

1.2.1 Optimal Incentive Regulation

Since the 1980s many countries reformed the regulation of some of their industries. This wave of reform stimulated not only a political, but also an economic debate on regulation. In countries like the UK and US many industries were reorganized, and sophisticated regulatory schemes were designed to give incentives to the firms in the industry. For example, in the UK electricity and rail industries the network has been separated from the generation of products that run through the network. In the US telecommunications industry Ma Bell has been split up into long-distance carrier AT&T and several local Baby Bells. Regulatory schemes range from cost-plus contracts to price caps. Recently regulators start refining the sophistication of their instruments. For example, the UK water regulator, Ian Byatt, publishes a league table of service performance for the water supply companies each year. He observes that:

> "*comparative competition may not make them quite like companies subject to market competition. But it can goad them to improved performance and the regulator has a responsibility to ensure that it is channelled into fruitful areas.*" [Byatt (1997)]

UK electricity regulator Stephen Littlechild introduced a so-called yardstick on electricity purchase costs. This would give the Regional Electricity Companies (RECs):

> "*a sharper incentive to control their electricity purchase costs, by limiting the amount of generation costs that they could pass through to customers.* [Littlechild] *considered the possibility of permitting the RECs to pass through to franchise customers only some type of 'yardstick' amount, such as the average cost of electricity purchased for franchise customers in England and Wales.*" [Office of Electricity Regulation (1996)]

Although the yardstick has not been implemented in practice, it plays a role in "providing information and facilitating regulation." In the next subsection we will discuss when these comparative regulatory schemes can be helpful for a regulator.

A standard problem in incentive regulation is the mechanism design problem of Baron and Myerson (1982). It derives the optimal regulatory scheme, consisting of a per-unit price and a lump sum transfer, that a regulator should offer to a regulated monopolist. Key elements of the problem are that there is a conflict of interest between the regulator and the regulated firm, and that the monopolist has private, non-verifiable information about his costs of production. Although the regulator can commit to a take-it-or-leave-it offer to the firm, he should respect the existing information asymmetry. Therefore he cannot do better than offering a regulatory scheme that is compatible with the monopolist's incentives. The best feasible scheme is one in which an efficient firm receives an informational rent, while it produces the efficient amount of the good. An inefficient firm receives a transfer that is just big enough to make it accept the offer, while it produces at a price higher than would be optimal without information asymmetries. Inefficient firms produce less than would be optimal without information asymmetry, to save informational rents for the efficient firm. Such a distortion of the symmetric information scheme due to the presence of asymmetric information is commonly observed in information economics.

The theory on optimal incentive regulation has blossomed since the seminal paper by Baron and Myerson. Recent text books on regulation, such as Armstrong *et al.* (1994), and Laffont and Tirole (1993), opened up many avenues for relevant research. The second chapter is in line with this theoretical literature.

1.2.2 Contribution of Chapter 2

In chapter 2 we analyze a problem of optimal incentives in which more then one input is needed to produce the final good. For the production of products, such as electricity, gas, and telephony, more inputs are needed to produce them. For electricity and gas we need both generation and distribution, while for long-distance telephony services we need both local and long-distance telephone services. The organization of the industry is a crucial choice for a regulator who wants to optimize social welfare. In chapter 2 of the thesis we study the choice between monopolistic and independent input supply for a product that requires two inputs.

The introduction of more inputs in the industry introduces two opposing effects to the analysis. Let us first introduce a second input supplier with production costs identical to those of the incumbent supplier. The incumbent produces the first input, while the second supplier produces the second input. Both inputs together create an output. Production cost is private information to each input supplier, and costs are perfectly positively correlated. Is the regulator's optimal scheme for two identical input suppliers similar to the scheme for one input supplier? No, in fact the regulator can exploit correlation and competition between independent suppliers and extract all rents. The seminal paper of Shleifer (1985) illustrates this. Although costs are private information, the regulator can extract both suppliers' rents and implement the social welfare maximizing scheme. He does this by offering the welfare maximizing scheme whenever both input suppliers report equal costs, while he punishes both firms when cost reports conflict. Each input supplier knows that both suppliers have the same costs of production. Hence, if one supplier expects that the second supplier tells the truth, it is best for himself to do the same. This kind of competition is called yardstick competition. In case of perfect correlation between costs, the regulator only needs a small punishment to implement the welfare maximizing outcome. For imperfect cost correlation only imperfect inferences between suppliers are possible. But sufficiently severe punishments for unlikely cost combinations can still implement the expected welfare maximizing outcome. The regulator compares the suppliers' cost reports, and fully extracts expected rents from suppliers by rewarding and punishing optimally on basis of suppliers' relative cost position.

The regulator's possibilities to fully extract suppliers' rents depend on two crucial factors. First, the regulator must be able to punish suppliers severely for some cost combinations. Severe *ex post* punishments need however not be realistic. Often firms are to some extent protected from severe punishments by limited liability law. In that case full rent extraction need no longer be feasible to the regulator.

Second, the argument of full rent extraction depends on the assumption that one supplier can infer something about the other supplier's cost after observing his own cost. That is, this argument depends on the assumption that costs are correlated. When costs are independently distributed, the yardstick competition effect disappears, and can no longer help the regulator to extract any rents from the industry. In that case, competition between two suppliers only hinders the regulator's welfare maximization. Because the inputs are complementary, prices are optimally set as a function of both suppliers' cost report. This creates an informational externality for independent input suppliers. In case input suppliers send cost reports independently, the regulator has to give an informational rent to both efficient input suppliers to prevent them from overstating their costs. Each independent input supplier can only imperfectly anticipate the cost of the other supplier. An independent input supplier does not internalize the externality that his report causes on the other supplier. When a monopolistic supplier knows both input's costs and coordinates his cost reports, the supplier internalizes this informational externality, and the regulator economizes on informational rents. The regulator only needs to pay rents to prevent overstatement of one of the input's costs. Therefore, for independent retailing costs the regulator extracts most rents from the input suppliers by letting them coordinate their cost reports. This informational externality is discussed in more detail by Gilbert and Riordan (1995).

In chapter 2 we apply the same line of argument to study the optimal incentive regulation of complementary inputs. A special feature of the model is that *ex post* punishments are infeasible, because the input producers are limitedly liable for losses they make. We give a characterization of the optimal regulatory scheme for any non-negative correlation between costs. And derive which organization of input production is optimizing expected social welfare. Given the line of argument of the previous two paragraphs, the following optimal organization should no longer be surprising. For sufficiently small correlation between costs, coordination between the input suppliers is best, while for big cost correlation competition between the input suppliers is best for expected social welfare. For substitutable products Dana (1993) analyzes an analogous trade-off, and obtains qualitatively identical results. However, the optimal regulatory schemes that implement the optimal organization of the industry differ substantially. We show this in chapter 2.

1.3 R&D Race with Learning Laboratories

In the previous section we assumed that the regulator can precommit to a scheme for an input supplier. This is a basic assumption we make in chapter 2. For a regulator such a strong assumption concerning commitment could be realistic. For other economic problems this assumption is too strong. In problems in which competing firms reveal information to each other, credible commitment to a scheme need not be realistic. We therefore drop the assumption on commitment in our analysis of strategic information revelation in research and development (R&D) races. In the next subsection we describe the basics of the problem of chapter 3, while the second subsection summarizes its main results.

1.3.1 Revenue Sharing and Strategic Revelation

In some major US sports leagues, such as the Major League Baseball (MLB) and the National Football League (NFL), teams share revenues. For example, in the MLB the top 13 revenue-generating teams contribute US$ 100m to the 15 teams with lowest revenues. For the National Hockey League revenue sharing is a hot issue in negotiations. Sports leagues share revenues between teams to create a level playing field among their teams. A match between two teams is exciting, and attracts many viewers, if the teams are of comparable strengths. Teams can achieve comparable strengths by investing comparable sums of money in talent. This is only possible when revenue differences among teams were not too big. Revenue sharing is a way to level the teams' revenue levels, and thereby attract more spectators and tv-money. Besides that, revenue sharing has another effect. An individual team knows that if it wins relatively much money, it has to share part of its revenues with a team of relative small fortune. If the team will perform badly, it knows that a strong team will cover part of the costs. This anticipation gives teams incentives to invest less in talent. That is, revenue sharing introduces free-rider effects among the league's members, which lowers wasteful overinvestments in sports talent.

Revenue sharing could play a similar role for competing firms in innovative industries too. One adverse effect of revenue sharing among competing firms is, however, that it could facilitate collusion among the firms. Therefore revenue sharing need not be a realistic arrangement among competing firms. The study of the incentive effects of revenue sharing should however be seen as a first step towards the study of effects of patent scope on firms' incentives to invest in R&D. A change in the revenue share redistributes revenues between firms, while the expected total revenue remains constant. One can therefore focus attention on the redistributional effects of a change in revenue share. A change of the patent scope has two effects on the industry. First, it redistributes revenues between firms. But, second, it also affects the expected total revenues of firms. This second effect should be incorporated in the analysis in order to study the effect of patent scope on the firms' R&D investments. The analysis of patent scope in R&D races awaits future research.

We study the effects of revenue sharing on incentives of firms that invest in research as well as development. Firms learn from research in the sense that they receive an imperfect, but informative signal about their costs of development after they invest in research. This affects firms' incentives to invest and share learned information greatly. The analysis of chapter 3 aims at understanding firms' incentives to invest in

R&D, and incentives to reveal signals. We focus on the effect of revenue sharing on investments and revelation.

Concerning information revelation there are two basic effects. For perfectly positively correlated development costs, one firm's signal gives his rival information about his own development cost. When a firm reports that it found good news, then its rival learns that its project is a good project too, and the rival becomes more optimistic about development costs. Therefore a low-cost message encourages a rival firm to invest in development. We call this effect the informational effect. An effect that opposes the informational effect is the strategic effect. When a firm sends a low-cost message, then its rival learns that this firm has low development cost and will invest aggressively in development. This discourages the rival's investments. The informational effect gives firms an incentive to reveal only bad news, while the strategic effect gives incentives in the opposite direction. For positively perfectly correlated development costs the informational effect dominates the strategic effect in most cases. When firms share part of their revenues with their rival, firms' incentives change. For big enough revenue share firms want to encourage their rival to invest in development. Firms like to free-ride on the revenue that is generated by their rival's augmented investments. Therefore, given the predominance of the informational effect, firms want to reveal only good news.

1.3.2 Contribution of Chapter 3

In chapter 3 we study an R&D race of two firms that work on the same project. Firms' costs of investment are therefore perfectly positively correlated. When the project is easy for one firm, it is easy for its rival too. This creates a big scope for a firm to learn from its rival about its own cost.

A big difference between chapter 3 and the previous subsection is that neither of the firms know initially whether they have good or bad information. How well a firm is informed about its cost is determined endogenously by its information acquisition investment. Such a problem of firms that learn while doing R&D was first studied by Choi (1991). Firms interact in an interesting manner because they can potentially learn from each other. Therefore firms underinvest in acquiring information when the acquired information is public. Each firm rather learns from its rival, than from its own investments. Firms incentives to invest in information acquisition are increased when they receive private signals. Firms can only rely on their own information. This gives bigger incentives to invest in development and to acquire information. In chapter 3 the interrelation between firms' investment decisions and beliefs is exposed in more detail.

What happens when a firm believes that its rival reports development costs truthfully? Then there is always a firm that wants to misrepresent its costs. When firms share little of their revenue, a firm wants to discourage its rival's development investments. It therefore has an incentive to always report bad news. For high revenue shares firms always want to report good news. When a firm believes the good news, it is encouraged to invest in development, and its rival will take a free ride on the firms increased investments. Analogous to Crawford and Sobel (1982) we can prove that since there is a conflict of interest between firms, information has a binary support, and communication is costless, no relevant information will be send by a firm. Since the sending firm has an incentive to misrepresent its costs, and it has no means to make its report credible, the receiver cannot take any information from the sender seriously. Each firm can therefore do no better than to ignore its rival's cost report, and choose the development investment that maximize its *ex ante* expected profit.

This negative result depends on the non-verifiability of firms' information. When a firm's information is verifiable, it only has a choice between disclosing its information or concealing it from its rival. In that case it is rational for its rival to be skeptical. This means that for low (resp. high) revenue shares it expects to face the most (resp. least) efficient firm with an incentive to conceal. This is consistent with a firm's incentives to conceal information, and this makes it optimal for the firm to reveal its costs completely. This unraveling result was discussed in the seminal contributions on strategic disclosure of verifiable information by Grossman (1981), Milgrom (1981), and Milgrom and Roberts (1986). For intermediate revenue shares both low- and high-cost firms have an incentive to conceal costs in our setup. Therefore there are no beliefs such that full disclosure is reached in equilibrium.

Both the incentives of firms to invest in R&D and incentives to reveal information are discussed in greater detail in chapter 3.

1.4 Disclosure Regulation and Correlation

In chapter 4 we study a problem that is similar to that of chapter 3. Again there are two competing firms that invest in information acquisition, decide how much to communicate to their rival, and invest in development. The interaction between the informational and strategic effect plays a major role in chapter 4 too. In the preceding two sections we assumed that information is known to the informed party with certainty. This resulted in powerful results concerning firms' incentives to reveal and disclose their private information. In this section we show how these extreme results break down when it is no longer certain whether or not a firm has private information about its retailing costs.

1.4.1 Partial Information Disclosure

In many innovative, high-tech industries, firms actively manage expectations of customers, investors, and competitors. It is easy to find examples of information management in the popular press. For example, The Economist observes the following on the management of biotech firms.

> "*Running a biotech company is like managing other high-growth industries such as information technology, only worse. For much of their first decade biotech firms live on promises rather than products, while their bright ideas make their way through pre-clinical and clinical trials. Sustaining investors' and employees' enthusiasm is a daunting task.*" [The Economist "European Biotech: Management Shortfall", 18/07/1998]

Firms can affect expectations of other agents in the industry by concealing or announcing information. The preannouncement of a new product could make customers, investors and competitors more optimistic about the potential introduction of the product in the market. In the industry for video game consoles, for example, Oliver Burkeman reports about Sony and Nintendo's product preannouncements after Sega's recent introduction of a new console:

> "*Few details of either machine, a successor to Sony's PlayStation, (...) and a new Nintendo console (...), have been made public yet. And in an industry noted for its obsessive deployment of bluff, counter-bluff and spoiling tactics, the battle lines are unlikely to be clear for some time yet.*" [The Guardian "Mortal Combat", G2-Europe, 03/09/1999]

In other instances it would be better for firms if they concealed intermediate successes on innovations. Product concealment would be a strategy for firms that work on intermediate innovations that are also useful for their rivals. The strategies of firms in a high-tech industry do not only concern the amount of money to invest and the direction in which research should proceed, but also what information to announce, and what to conceal. A general lesson from this brief introduction to the issue, drawn by The Economist, is that:

> "*The lesson for the bosses of Britain's current breed of high-tech companies is that in addition to their scientific and financial skills, there is another vital skill they need – that of managing expectations.*" [The Economist "Biotech Blooms", 25/05/1996]

In chapter 4 we study in more detail how active expectation management affects firms' investments in research and development.

Seminal contributions on strategic disclosure of verifiable information are Grossman (1981), Milgrom (1981), and Milgrom and Roberts (1986). A basic property of their problems is that it is known that the sender of information is informed, and information is costlessly verifiable. The basic result here is that the uniformed party (the receiver) forms sceptical equilibrium beliefs, that forces the sender to fully disclose his information in equilibrium. If the receiver expects the worst consistent with the sender's disclosure, this is consistent with the sender's incentives to disclose and conceal information, and given these beliefs it is best to disclose. This powerful result is called the "unraveling result". In Okuno-Fujiwara *et al.* (1990) sufficient conditions for the unraveling result between competing parties are found.

The unraveling result is weakened by the introduction of uncertainty about whether or not the sender is informed. Although information is still verifiable, it is no longer verifiable whether or not the sender is informed. This uncertainty disables the unraveling result in most cases. Austen-Smith (1994) shows that when the receiver is uncertain about the informedness of the sender, the sender can conceal some of his information in equilibrium. Typically, uncertainty about the informedness of the sender enables an informed sender with bad information to pool with his uninformed counterpart. In equilibrium only partial disclosure occurs. Good news is disclosed while bad news is concealed from the financial market. This argument is generalized and refined by Shin (1994). Recently Krishnan *et al.* (1996) provide empirical evidence that firms partially disclose earnings information to the financial market. We will use a similar framework of uncertain informedness to study strategic disclosure by racing R&D laboratories.

The approach of chapter 4 is to assume that firms do not always learn. It is therefore not known whether or not firms are informed. When a firm discloses its information, this is verifiable, but when a firms claims to be uninformed, this is not verifiable. Uncertainty about a firm's informedness causes a break-down of the unraveling result, because an informed firm that does not want to disclose its information can pool with the uninformed firms.

In the fourth chapter of this thesis we apply and extend this basic economic insight in a dynamic model of R&D competition. We give an overview in the next subsection.

1.4.2 Contribution of Chapter 4

In chapter 4 of this thesis research laboratories partially disclose information too. However the conditions under which partial disclosure occurs, and the kind of information that is eventually disclosed are sensitive to the particular context in which firms operate. There are two main causes for this.

First, there is strategic interaction between the sender and receiver after information exchange. Firms disclose and conceal information in anticipation of the effects that the disclosure and concealment will have on later competition. Competing firms have in general an incentive to make their rival as pessimistic about his possibilities of successfully completing his innovation. When firms can learn most from each other, i.e. future costs are perfectly correlated, they have an incentive to make their rival as pessimistic as possible about their discoveries. Firms disclose bad news and conceal good news in general. But since firms interact strategically, there are also extreme cases in which firms have an incentive to unilaterally disclose good, or conceal bad information to manipulate their rival's beliefs. When firms' future costs are not related to each other, i.e. future costs are independent, then firms make their rival pessimistic about his future potential by disclosing good news about themselves. This means that correlation between development costs crucially affects the contents of firms' disclosures. Cost correlation is the first main topic of the fourth chapter.

Second, not only do disclosure and concealment of information affect future competition, but it also affects firms' incentives to acquire information. The uncertainty of being informed is determined by firms' information acquisition investments. The incentives to acquire information are affected by the correlation between development costs, and disclosure regulation. We compare two regimes of information disclosure. In the first firms are required to disclose information. Under that regime firms with perfectly correlated development costs free-ride on each other's information as in chapter 3. Consequently, firms acquire less information than is efficient. Under voluntary disclosure firms partially disclose. Firms with perfectly correlated costs have to rely more on themselves for information, which increases their incentives to acquire information. For firms with identical independently distributed development costs we observe different effects. First, under mandated disclosure firms cannot learn from their rival about own costs of development. Consequently there are no free-rider incentives for information acquisition. Generically firms have an incentive to overinvest in information acquisition, while under voluntary disclosure firms' equilibrium information acquisition investments are even bigger. The effects of disclosure regulation on firms' incentives to invest in R&D are studied in chapter 4 in greater detail.

These are the main contributions, and will be the main parts of the discussion in chapter 4.

1.5 Organization of the thesis

The remainder of the thesis is organized as follows. Part I, that consists of chapter 2, presents a problem of regulating complementary input supply. It analyzes how limited liability and cost correlation affect the optimal organization of an industry in which complementary inputs are produced. Part II consists of two chapters on incentive problems in dynamic research and development competition. Incentive problems occur in the acquisition and revelation of information, and in the development of the innovation. In the first chapter, i.e. chapter 3, our focus is on the effects of revenue sharing and strategic information revelation on investments in research and development. Part II closes with chapter 4 that focuses on the effects of disclosure regulation and cost correlation on firms' R&D investments and information disclosure. The chapters of this thesis can be read independently from each other.

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Part I

Optimal Regulatory Design

Introduction to Part I

In this part of the thesis we analyze a problem of optimal regulatory design. Key feature of the problem is that there is asymmetric information between the regulator and the industry on the costs of production. Because firms have superior information and different interests than the regulator, the regulator has to give firms financial incentives to make them produce optimally. The industry produces two complementary goods. The regulatory problem is to organize the industry such that firms' incentives for truthful information revelation and participation are obtained at minimal social cost. The regulator chooses between a monopolist who produces two products, and two independent producers who produce one product each. Besides the organization of the industry, the regulator chooses subsidies and the probability with which the final product is produced.

For the choice between monopolistic and independent production the regulator trades off two effects. On the one hand the regulator can save information rents by comparing the cost reports of two independent firms, and making the regulatory instruments dependent on this comparison. When the costs are correlated, the cost of one firm gives an indication of the costs of the other firm. In that case the regulator can economize on a part of the subsidy. The stronger the correlation, the sharper the indication that costs give about each other, and the more subsidy can be saved. We call this effect the yardstick competition effect. Because a monopolist can coordinate his cost reports, incentives based on a cost comparison are useless. On the other hand the regulator can save subsidies because a monopolistic producer can coordinate his cost reports. When independent producers overstate their costs, they cause an externality on each other. If it would be known that one firm overstates its cost, the other firm would have a lower incentive to overstate its cost too. Independent firms cannot coordinate their reports in such a way, and they need higher subsidies to overcome this externality. A monopolistic producer internalizes this externality, which saves subsidies for the regulator. We call this the internalization effect. Both the cost correlation and the firms' liability affect the trade-off between these two effects. A regulated industry with limitedly liable firms is optimally organized as follows. For low correlation the regulator chooses monopolistic production, because the internalization effect dominates, while for high correlation independent producers are better for welfare. In chapter 2 we discuss these two effects in more detail, and characterize the optimal regulatory instruments that embody these effects.

Chapter 2

Regulating Complementary Inputs

2.1 Introduction

In most regulated industries the production of final output requires the production of more than one input. For example, for public utilities production and distribution are two distinct activities. In the telecom industry long-distance and local telephony services can be distinguished. Moreover, these inputs are perfectly complementary goods that are used in fixed proportions to produce the final output. Traditionally, final output is supplied by a regulated monopolist that produces both inputs. In the 1980s and 1990s, several countries decided to break up some of these monopolies. For example, in the US telecommunication market the long-distance telephony supply was separated from local telephony supply, and the supply of local telephone services was delegated to local monopolies. The new AT&T provides long-distance services and several Baby Bells serve the local markets.[1] In many European countries the incumbent PTTs still provide both local and long-distance telephone services.

In this setting a regulator faces the following organizational choice. Either all inputs are produced by one multi-product monopolist, or each input is produced by an independent input producer. A change of the industry's organization changes incentives of the industry's firms. The regulator can use this fact by choosing the firm's organizational structure such that the producers' incentives are best suited for maximizing social welfare. This regulatory choice is studied in this chapter.

We abstract from technological reasons for choosing a certain organization of input supply. If the regulator would be fully informed about the inputs' production costs, and if he would have enough regulatory instruments, the firm's organizational

[1] The 1996 Telecommunications Act has allowed the Baby Bell in the long-distance telecom market, but this has not effectively changed the market structure so far.

structure would not matter. However, in a more realistic setting, the regulator is not completely informed about the input producers' costs. In order to receive truthful cost messages from the input supplier(s), the regulator has to pay the supplier(s) socially costly informational rents. To economize on these transfers, the regulator must commit to refrain from production in more states of nature than would otherwise be socially desirable. In the second-best solution, the regulator trades off the social cost of transfers against allocative efficiency. In such a situation the organization of input supply matters.

There are two conflicting effects at work. First, there is the "informational externality" effect, which is studied by Baron and Besanko (1992) and Gilbert and Riordan (1995). When one producer overstates his cost, this decreases the other producer's incentive to overstate his cost. Since independent input suppliers do not learn each other's cost message at the moment of message sending, the input producers are not able to correct their messages for this externality. Under monopolistic input supply the monopolist internalizes this externality. This gives the monopolist less incentives to overstate the individual input production costs. Therefore, the regulator saves informational rents by choosing monopolistic input supply. Second, there is the yardstick competition effect, as studied by Nalebuff and Stiglitz (1983) and Shleifer (1985). When production of the two inputs requires comparable technologies, the costs for providing these inputs is likely to be correlated. In that case, under independent input production each producer's cost message to the regulator gives some information about the other producer's cost. The regulator can exploit this fact by punishing the producers for sending messages that give unlikely cost combinations and by rewarding more likely ones. Thereby the regulator can extract some of the producers' surplus. Because a monopolistic input supplier can coordinate his cost messages, such a scheme does not work under monopolistic input supply.

Dana (1993) studies a similar organizational problem in a model where the goods supplied are substitutes. The paper by Dana shows that for low enough correlation coefficients, monopolistic input supply is the regulator's optimal choice. For all other values of the correlation coefficient the yardstick competition effect still dominates. As we observed, there are important regulated industries in which the goods supplied are complements. In this chapter we study the optimal regulatory scheme for these industries both under monopolistic and independent input supply. We show that a similar result holds true for an industry with perfectly complementary goods. The regulatory schemes that underpin the optimal organization of input supply, however, are quite different from that in Dana (1993). When inputs are needed in fixed proportions to produce the output, it would be socially wasteful to choose a regulatory scheme that does not respect these proportions. This means that quantity discrimination between independent input suppliers is not desirable. Therefore the regulator must rely more on the transfers to discriminate between independent suppliers.

The optimal regulatory scheme under independent input supply differs from that under monopolistic supply. Especially for highly correlated costs the optimal scheme under independent input supply is not monotonous in total costs, and, therefore, not feasible under monopolistic input supply. This then gives rise to the yardstick competition effect. The occurrence of the yardstick competition effect depends on the regulator's possibility of punishing producers for sending unlikely (and unfavorable) cost messages. The regulator punishes a producer by letting him earn low profits or even suffer losses in some instances. The extent to which the regulator can force producers to suffer losses depends on the extent to which producers are protected by liability rules. We say that a producer's liability is limited when that producer cannot be forced to bear realized losses as a consequence of participating in the regulatory contract. This definition corresponds to limited zero-liability contracts as in Sappington (1983) and imposes an *ex post* participation constraint on the regulatory contract.

When producers have unlimited liability, they can be forced to bear *ex post* losses. Both Crémer and McLean (1985) and Demski and Sappington (1984) show that, under assumptions similar to ours — risk-neutral regulator and producers, positively correlated costs, and a binary support for the producers' state variables — the regulator can achieve the first-best solution under independent input supply.[2] He does this by punishing both producers severely in unlikely cost states. Under monopolistic input supply, he can only reach a second-best solution (Baron and Myerson, 1982). That is, under unlimited liability, the yardstick competition effect dominates the "informational externality" effect for all positive correlation coefficients.

In order to fully extract producers' rents, the regulator must force the producers to bear *ex post* losses for unlikely cost combinations. For small, but positive correlation between the costs, the scheme that implements the first-best solution relies on severe

[2]These models study full rent extraction when products are substitutes. Similar optimal schemes are applicable when products are complementary. An exception to this regularity is the model described by Auriol and Laffont (1992). In that model the first-best solution is not reached for intermediate degrees of correlation because it contains an independently distributed cost component, besides a correlated one.

ex post losses. When producers are protected by limited liability, they cannot be forced to bear such losses. In that case the smaller the correlation between costs, the bigger the extent to which the regulatory scheme differs from the full rent extracting scheme. Therefore, the smaller the cost correlation, the smaller the extracted rents, and the weaker the yardstick competition effect.

If costs are independently distributed, there is no yardstick competition effect, while the "informational externality" effect still holds. Then under both limited and unlimited liability, monopolistic input supply is the best organizational choice for a regulator. This is illustrated in Baron and Besanko (1992) and Gilbert and Riordan (1995), respectively.

If costs are perfectly correlated, the distinction between limited and unlimited liability disappears. In this situation the yardstick competition effect clearly dominates the "informational externality" effect. Moore (1992) shows that the first-best can be uniquely implemented under independent input supply.[3]

Recent studies analyze the optimal organization of regulated industries in different settings. Severinov (1997) studies how the optimal industrial organization of firms with independently distributed private information on production costs depend on the substitutability of products. Iossa (1999) studies optimal organization in a model in which firms have private information about a demand intercept. Jeon (1998), and Laffont and Martimort (1997) endogenize the cost of independent input supply by considering collusion between agents. And Dalen (1998) compares firms' incentives to invest in process innovation in a setting with correlated private cost information.

The chapter is organized as follows. The model of optimal organizational choice is described in section 2. In section 3 we derive the equilibrium choices of the regulator and the input producers given the choice on the organization of input production. A comparison between monopolistic and independent input supply is made in section 4. Section 5 concludes the chapter.

2.2 The Model

The players of the regulation game are the regulator, and the production units of input 1 and 2. The production of one unit of an indivisible output with social value

[3] In order to obtain uniqueness, multi-stage mechanisms in combination with the subgame perfect equilibrium refinement are necessary. Multi-stage mechanisms are not studied in this paper. Nalebuff and Stiglitz (1983) and Shleifer (1985) show that the truth-telling first-best is one of the equilibria of the optimal mechanism.

V requires the supply of one unit of input 1 and one unit of input 2. The cost of producing input i, θ_i ($i = 1, 2$), can be either high, $\overline{\theta}$, or low, $\underline{\theta}$, with $0 < \underline{\theta} < \overline{\theta}$. The players play a 5-stage game with incomplete information. Chronologically, the following choices are made.

In the first stage of the game the regulator chooses either monopolistic or independent input supply. This decision induces two subgames: the subgame after choosing monopolistic input supply, and the subgame for independent input supply. These subgames are defined in the remainder of this section.

In the *monopolistic input supply* (MIS) subgame, the regulator sets a transfer scheme $T : \{2\underline{\theta}, \underline{\theta} + \overline{\theta}, 2\overline{\theta}\} \rightarrow \Re$ that specifies the transfer from the regulator to the monopolist in case the monopolist's report on total cost of production is $2\underline{\theta}$, $\underline{\theta} + \overline{\theta}$ and $2\overline{\theta}$, respectively. The transfer is not conditional on whether or not production takes place. Furthermore, the regulator lets production occur with probability $Q^M : \{2\underline{\theta}, \underline{\theta} + \overline{\theta}, 2\overline{\theta}\} \rightarrow [0, 1]$.[4]

Nature chooses the costs for producing input 1 and 2 in the third stage of the game by drawing these costs from a symmetric probability density. The prior probabilities are shown in Table 2.1. In this table we depict prior probabilities $\Pr[\theta_1, \theta_2]$, for $\theta_1, \theta_2 \in \{\underline{\theta}, \overline{\theta}\}$.

θ_2 \ θ_1	$\underline{\theta}$	$\overline{\theta}$
$\underline{\theta}$	p^L	q
$\overline{\theta}$	q	p^H

[Table 2.1: prior probabilities]

Note that the correlation coefficient is $\rho = \frac{p^L p^H - q^2}{(p^L + q)(p^H + q)}$. This means that when $q = \sqrt{p^L p^H}$ the production costs of the inputs are independently drawn from the distribution. When $q = 0$ there is perfect positive correlation between the production

[4]It suffices to focus attention to a regulatory scheme that depends on total reported costs $\widetilde{\Theta} = \widetilde{\theta}_1 + \widetilde{\theta}_2$ only, since the inputs are perfect complements. Because the inputs are produced in fixed proportion, the incentives of the regulator as well as the monopolist are symmetric in the components' costs. If the regulator would offer an asymmetic scheme, either the monopolist, or himself would be better off choosing only one of the schemes for $(\underline{\theta}, \overline{\theta})$ as well as $(\overline{\theta}, \underline{\theta})$. The regulator can therefore do no better than offering a scheme that is symmetric in cost reports.

In a model with divisible output, choosing $Q^M(.)$ would be regulation of quantities. In a fully regulated industry regulated quantity is in a one-to-one relation to price through consumers' demand. Then regulation of $Q^I(.)$ is equivalent to price regulation. Due to the linearity of the present model, it is optimal for the regulator to either require or forbid production with probability one.

costs of the inputs. We assume that $\rho \geq 0$, or $0 \leq q \leq \sqrt{p^L p^H}$. The monopolist learns the production costs of both inputs, θ_1 and θ_2.The regulator is not informed about the production costs of input 1 and 2.

Due to the revelation principle (e.g. see Myerson 1982, Proposition 2), the regulator can focus on direct revelation mechanisms without loss of generality. Given the regulatory scheme, the monopolist sends a message about his total cost to the regulator in the fourth stage of the game. The monopolist sends message $\widetilde{\Theta} \in \{2\underline{\theta}, \underline{\theta}+\overline{\theta}, 2\overline{\theta}\}$, and the regulator's instruments are a function of these messages, $\{T(\widetilde{\Theta}), Q^M(\widetilde{\Theta})\}$.

Given these instruments and his cost message, the monopolist decides whether or not to participate in the regulatory scheme in the fifth stage of the game. In case he decides not to participate, he gets zero profits. Whenever the monopolist chooses to participate, the scheme is implemented in the last stage of the game.

Given the regulator's first-stage choices, and the second-stage private information, the monopolist maximizes his expected profit. The regulator maximizes expected social welfare, which is defined as the sum of total expected profits and the net consumers' surplus, allowing for distributional distortions caused by taxes. If the monopolist participates in the scheme, then social welfare is defined as:

$$W^M(\widetilde{\Theta}, \Theta) = VQ^M(\widetilde{\Theta}) - (1+\lambda)T(\widetilde{\Theta}) + \Pi(\widetilde{\Theta}, \Theta)$$

where V is the social value of the produced output, λ represents the social cost of public funds,[5] and the monopolist's expected profit is:

$$\Pi(\widetilde{\Theta}, \Theta) = T(\widetilde{\Theta}) - \Theta Q^M(\widetilde{\Theta}),$$

with $\Theta, \widetilde{\Theta} \in \{2\underline{\theta}, \underline{\theta}+\overline{\theta}, 2\overline{\theta}\}$.

In the *independent input supply* (IIS) subgame, the regulator sets a transfer scheme $(t^1, t^2) : \{\underline{\theta}, \overline{\theta}\} \times \{\underline{\theta}, \overline{\theta}\} \rightarrow \Re \times \Re$ with transfers from the regulator to the producer of input 1 and 2, respectively. Furthermore he chooses a probability of production $Q^I : \{\underline{\theta}, \overline{\theta}\} \times \{\underline{\theta}, \overline{\theta}\} \rightarrow [0, 1]$. The input production costs are drawn from the same prior probability distribution as under MIS. Each producer is privately informed about his own cost, while communication between the two input producers about their costs is not possible. The regulator is not informed about the production costs of input 1 and 2. Given the regulatory scheme, the input producers simultaneously send a message about their costs to the regulator in the fourth stage of the game. Input producer i

[5]In some other models of regulatory economics, e.g. Baron and Myerson (1982), social welfare is defined as the weighted sum of consumers' surplus and industry's profits, $W = VQ + \alpha\Pi$, with $0 \leq \alpha < 1$. Such specification gives similar qualitative results.

sends message $\widetilde{\theta}_i$ for $i = 1, 2$, and the regulator's instruments are a function of these messages, $\{t^1(\widetilde{\theta}), t^2(\widetilde{\theta}), Q^I(\widetilde{\theta})\}$, where $\widetilde{\theta} = (\widetilde{\theta}_1, \widetilde{\theta}_2) \in \{\underline{\theta}, \overline{\theta}\} \times \{\underline{\theta}, \overline{\theta}\}$.

In the fifth stage of the game the input producers learn each others' costs and decide whether or not to participate in the regulatory scheme. This stage reflects the producers' limited liability. Unlimitedly liable producers would have to make their participation decision in the third stage of the game on basis of interim profit evaluation. If one input producer decides not to participate, both producers receive zero profit; if both input producers choose to participate, the regulatory scheme is implemented.

Given the regulator's first-stage choices and the second-stage private information, each input producer maximizes his expected profit. If both input producers participate in the scheme, social welfare is defined as:

$$W^I(\widetilde{\theta}, \theta) = VQ^I(\widetilde{\theta}) - (1+\lambda)[t^1(\widetilde{\theta}) + t^2(\widetilde{\theta})] + [\pi_1(\widetilde{\theta}, \theta) + \pi_2(\widetilde{\theta}, \theta)],$$

and firm i's expected profit is:

$$\pi_i(\widetilde{\theta}, \theta) = t^i(\widetilde{\theta}) - \theta_i Q^I(\widetilde{\theta}), \text{ with } \theta = (\theta_1, \theta_2) \text{ and } i = 1, 2.$$

A sketch the timing of the game is depicted in Table 2.2. Denote the monopolist by M, and independent input supplier 1 (resp. 2) by I1 (resp. I2).

$t = 1.1$	Regulator: MIS	Regulator: IIS
$t = 1.2$	Regulator: $\{T(.), Q^M(.)\}$	Regulator: $\{t^1(.), t^2(.), Q^I(.)\}$
$t = 2$	M learns costs: $(\theta_1, \theta_2) \in \{\underline{\theta}, \overline{\theta}\}^2$	I1 learns cost $\theta_1 \in \{\underline{\theta}, \overline{\theta}\}$ I2 learns cost $\theta_2 \in \{\underline{\theta}, \overline{\theta}\}$
$t = 3$	M sends message: $\widetilde{\Theta} \in \{2\underline{\theta}, \underline{\theta} + \overline{\theta}, 2\overline{\theta}\}$	I1sends message: $\widetilde{\theta}_1 \in \{\underline{\theta}, \overline{\theta}\}$ I2 sends message: $\widetilde{\theta}_2 \in \{\underline{\theta}, \overline{\theta}\}$
$t = 4$		I1,I2 learn each others costs I1,I2 accept/reject scheme
$t = 5$	Implement scheme	Implement scheme

[Table 2.2: sequence of moves]

We solve the game backwards. In the next section we solve the game up to the regulator's industrial organization choice. Section 4 closes the model's analysis by characterizing the optimal organizational choice for the regulator.

2.3 Solving the Subgames

In this section we study the equilibrium strategies of the regulator and input producer(s) given the organization of input supply. In the first subsection we characterize the equilibrium strategies under monopolistic input supply. The second subsection characterizes the equilibrium strategies under independent input supply. All proofs are relegated to the Appendix.

2.3.1 Monopolistic Input Supply (MIS)

The regulatory problem under MIS is similar to that in Baron and Myerson (1982). This means that the regulator faces the following mechanism design problem:

$$\max_{\{T(.),Q^M(.)\}} . \; E_\Theta\{W^M(\Theta,\Theta)\}$$

s.t.

$$\Pi(\Theta,\Theta) \geq \Pi(\widetilde{\Theta},\Theta) \tag{2.1}$$

$$\Pi(\Theta,\Theta) \geq 0, \text{ for all } \Theta,\widetilde{\Theta} \in \{2\underline{\theta},\underline{\theta}+\overline{\theta},2\overline{\theta}\}. \tag{2.2}$$

Inequality (2.1) is the incentive compatibility constraint, which states that it is optimal for the monopolist to reveal its true costs. Inequality (2.2) is the monopolist's participation constraint. A regulatory scheme that satisfies both (2.1) and (2.2), is called feasible. In this standard setting the regulatory instrument scheme is feasible if and only if the probability with which production occurs is non-increasing in the monopolist's cost message, i.e., $0 \leq Q^M(2\overline{\theta}) \leq Q^M(\underline{\theta}+\overline{\theta}) \leq Q^M(2\underline{\theta}) \leq 1$.

Given a non-increasing probability of the production scheme, we can easily derive the optimal transfers.

Lemma 2.1 *For MIS the optimal transfers are such that they reimburse the monopolist's expected cost and give him an informational rent that is non-increasing in his costs:*

$$T(C) = \Theta Q^M(\Theta) + (\overline{\theta}-\underline{\theta}) \sum_{\widetilde{\Theta}>\Theta} Q^M(\widetilde{\Theta}), \; \textit{for } \Theta \in \{2\underline{\theta},\underline{\theta}+\overline{\theta},2\overline{\theta}\}.$$

Analogous to Baron and Myerson (1982), this second-best transfer scheme is non-increasing in the monopolist's cost message.

After substituting for the optimal transfers in the expected welfare function, the maximization problem becomes:

$$\max_{\{Q^M(.)\}} \{Q^M(2\overline{\theta})p^H w^M(2\overline{\theta}) + Q^M(\underline{\theta}+\overline{\theta})2qw^M(\underline{\theta}+\overline{\theta}) + Q^M(2\underline{\theta})p^L w^M(2\underline{\theta})\}$$
$$\text{s.t. } 0 \leq Q^M(2\overline{\theta}) \leq Q^M(\underline{\theta}+\overline{\theta}) \leq Q^M(2\underline{\theta}) \leq 1,$$

with

$$w^M(\Theta) = V - (1+\lambda)\Theta - \lambda\frac{\Pr[\theta_1+\theta_2<\Theta]}{\Pr[\theta_1+\theta_2=\Theta]}(\overline{\theta}-\underline{\theta}), \text{ for } \Theta \in \{2\underline{\theta}, \underline{\theta}+\overline{\theta}, 2\overline{\theta}\},$$

the "virtual welfare" at cost Θ, i.e., the social value of the output minus the social costs of production minus informational rents. Because informational rents are non-negative, the second-best probabilities of production are such that in some cases production does not occur despite the fact that it would be desirable in the first-best. The probability scheme trades off allocative efficiency and informational rent saving.

It is easily verified that the "virtual welfare" is non-increasing in production costs for probabilities q that exceed the critical value:

$$q^M = \frac{p^H(1-p^H)}{2(p^H\frac{1+\lambda}{\lambda}+1)}.$$

At the optimum, production takes place whenever the "virtual welfare" is non-negative, which gives a non-increasing probability scheme. This is stated in the following lemma.

Lemma 2.2 *For MIS and $q \geq q^M$, production takes place with certainty whenever the "virtual welfare" is positive, and there is no production otherwise:*

$$Q^M(\Theta) = \begin{cases} 1, & \text{if } w^M(\Theta) \geq 0 \\ 0, & \text{otherwise} \end{cases}, \text{ for } \Theta \in \{2\underline{\theta}, \underline{\theta}+\overline{\theta}, 2\overline{\theta}\}.$$

For lower values of q (high correlation) the "virtual welfare" is no longer monotonous in costs, since $w^M(\underline{\theta}+\overline{\theta}) < w^M(2\overline{\theta})$. Analogous to Myerson (1981) the solution is found by equalizing the probabilities of production for costs $(\underline{\theta}+\overline{\theta})$ and $2\overline{\theta}$, and maximizing expected welfare given that constraint. This is stated in the following lemma.

Lemma 2.3 *For MIS and $q < q^M$, (i) if both production units have low costs, production takes place with certainty whenever the "virtual welfare" is positive:*

$$Q^M(2\underline{\theta}) = \begin{cases} 1, & \text{if } w^M(2\underline{\theta}) \geq 0 \\ 0, & \text{otherwise,} \end{cases}$$

(ii) for other cost combinations, production takes place with certainty whenever the conditional expected "virtual welfare" of production, given at least one high cost production unit, is positive:

$$Q^M(\underline{\theta}+\overline{\theta}) = Q^M(2\overline{\theta}) = \begin{cases} 1, \text{ if } 2qw^M(\underline{\theta}+\overline{\theta}) + p^H w^M(2\overline{\theta}) \geq 0 \\ 0, \text{ otherwise.} \end{cases}$$

In the next subsection we analyze the optimal regulatory scheme under independent input supply.

2.3.2 Independent Input Supply (IIS)

The regulatory problem under IIS is related to that in Dana (1993). While Dana studies an industry with substitutable inputs, we study complementary input supply. Since the inputs are needed in fixed proportions to produce the output, it would be socially wasteful to choose discriminatory probabilities of production. This reduces the number of instruments that the regulator can use effectively. The regulator solves the following mechanism design problem:

$$\max_{\{t^1(.),t^2(.),Q^I(.)\}} E_\theta\{W^I(\theta,\theta)\}$$

s.t.

$$E_{\theta_j}\{\pi_i(\theta,\theta)\} \geq E_{\theta_j}\{\pi_i[(\widetilde{\theta}_i,\theta_j),\theta]\}, \text{ for all } i,j=1,2,\ j\neq i, \text{ and } \theta_i,\widetilde{\theta}_i \in \{\underline{\theta},\overline{\theta}\} \tag{2.3}$$

$$\pi_i(\theta,\theta) \geq 0, \text{ for all } i=1,2, \text{ and } \theta_1,\theta_2 \in \{\underline{\theta},\overline{\theta}\}. \tag{2.4}$$

Inequalities (2.3) are the input producers' incentive compatibility constraints. The regulatory instruments induce truthful cost revelation in Bayesian equilibrium. Restriction (2.4) is the *ex post* participation constraint. Due to the limited liability assumption, an input producer must receive non-negative profits in all states of nature to induce his participation.

The regulator must give a low-cost input producer an informational rent that eliminates the producer's incentive to overstate his cost. Also for this problem there is a critical value, q^I, above which the "virtual welfare" is non-increasing in total production costs. This critical value is equal to:

$$q^I = \frac{1}{4}\sqrt{p^H}\left\{\sqrt{p^H\left(1+\frac{6}{\lambda}+\frac{1}{\lambda^2}\right)+8} - \sqrt{p^H}\left(\frac{1+3\lambda}{\lambda}\right)\right\}.$$

Notice that $q^I \leq \frac{1}{3}(1-p^H)$.[6] For $q \geq q^L$ (relatively low correlation between producers' costs) the transfer scheme is similar to the monopolistic input supply scheme, which is stated in the following proposition.

Proposition 2.1 *For IIS and $q \geq q^I$ the optimal transfers are such that they reimburse the producers' expected costs and they give an informational rent to each low-cost producer:*

$$t^1(\theta_1, \theta_2) = \theta_1 Q^I(\theta_1, \theta_2) + (\overline{\theta} - \underline{\theta}) \sum_{\widetilde{\theta}_1 > \theta_1} Q^I(\widetilde{\theta}_1, \theta_2), \text{ for } \theta_1, \theta_2 \in \{\underline{\theta}, \overline{\theta}\}.$$

Producer 2 receives similar transfers.

These transfers do not implement truth-telling in a unique Bayesian equilibrium. For each producer with low cost, $\underline{\theta}$, the transfer scheme makes him indifferent between truth-telling and cost overstating, irrespective of the other producer's message sending strategy. We can avoid "bad" equilibria and approximately maintain the optimal expected welfare level by slightly changing the regulatory scheme. This is stated in the following proposition.

Proposition 2.2 *Define $\Delta\theta = \overline{\theta} - \underline{\theta}$. For IIS and $q \geq q^I$ the regulator can stay arbitrarily close to the optimal welfare level and induce truthful revelation of the producers' costs as a (interim) dominant strategies Bayesian equilibrium, by making the following changes to the optimal regulatory scheme.*
Increase $t^1(\underline{\theta}, \underline{\theta})$, $t^1(\underline{\theta}, \overline{\theta})$ $t^2(\underline{\theta}, \underline{\theta})$ and $t^2(\overline{\theta}, \underline{\theta})$ with $\varepsilon > 0$, and take $\delta > 0$.
(i) If $Q^I(.) = 0$, choose $Q^I(\underline{\theta}, \underline{\theta}) = 2(\frac{\varepsilon}{\Delta c} + \delta)$ and $Q^I(\underline{\theta}, \overline{\theta}) = Q^I(\overline{\theta}, \underline{\theta}) = \frac{\varepsilon}{\Delta c} + \delta$.
(ii) If only $Q^I(\underline{\theta}, \underline{\theta}) = 1$, choose $Q^I(\underline{\theta}, \overline{\theta}) = Q^I(\overline{\theta}, \underline{\theta}) = \frac{\varepsilon}{\Delta c} + \delta$.
(iii) If only $Q^I(\overline{\theta}, \overline{\theta}) = 0$, choose $Q^I(\underline{\theta}, \overline{\theta}) = Q^I(\overline{\theta}, \underline{\theta}) = 1 - (\frac{\varepsilon}{\Delta c} + \delta)$.
(iv) If $Q^I(.) = 1$, choose $Q^I(\underline{\theta}, \overline{\theta}) = Q^I(\overline{\theta}, \underline{\theta}) = 1 - (\frac{\varepsilon}{\Delta c} + \delta)$ and $Q^I(\overline{\theta}, \overline{\theta}) = 1 - 2(\frac{\varepsilon}{\Delta c} + \delta)$.

For lower q (high correlation) the regulator rewards producers by paying them informational rents only if they both report low costs, but not otherwise. This gives the producers optimal incentives to reveal their costs. This is stated by the following proposition.

[6] Since q^I increases in λ, it suffices to check whether $\lim_{\lambda \to \infty} q^I = \frac{1}{4}\sqrt{p^H}(\sqrt{p^H + 8} - 3\sqrt{p^H}) \leq \frac{1}{3}(1 - p^H)$. That is, $\frac{1}{12}[3\sqrt{p^H(p^H + 8)} - (4 + 5p^H)] \leq 0$. Since this function increases in p^H, and for $p^H = 1$ the function equals 0, $q^I \leq \frac{1}{3}(1 - p^H)$ is established. Note that $q < q^I \leq \frac{1}{3}(1 - p^H)$, is equivalent to $q < p^l$.

Proposition 2.3 *For IIS and $q < q^I$ the optimal transfers reimburse each producer's expected cost and give an informational rent only if both producers report low production costs:*

$$\begin{aligned} t^1(\underline{\theta},\underline{\theta}) &= \underline{\theta}Q^I(\underline{\theta},\underline{\theta}) + (\overline{\theta}-\underline{\theta})[Q^I(\overline{\theta},\underline{\theta}) + \frac{q}{p^L}Q^I(\overline{\theta},\overline{\theta})] \\ t^1(\theta_1,\theta_2) &= \theta_1 Q^I(\theta_1,\theta_2), \text{ for } (\theta_1,\theta_2) \neq (\underline{\theta},\underline{\theta}). \end{aligned}$$

Producer 2 receives similar transfers.

These transfers do not implement truth-telling in an (interim) dominant strategy Bayesian equilibrium. Moreover, dominance cannot be obtained by means of arbitrary small changes in the regulatory scheme. This is stated in the following proposition.

Proposition 2.4 *For IIS and $q < q^I$ an arbitrary small change in the optimal regulatory scheme does not give truth-telling as a Bayesian equilibrium in (interim) dominant strategies whenever $Q^I(\overline{\theta},\overline{\theta}) > 0$.*

Since a Bayesian equilibrium cannot be obtained in dominant strategies, the cost messages that producers send to the regulator will depend on their expectations about the other producer's cost message strategy. This problem could be overcome by using non-direct revealing mechanisms, as in Moore (1992).

Propositions 2.2 and 2.4 imply that the possibility of implementation of the optimal expected welfare level by dominant strategies, depends on q. Whenever producers' costs are only slightly correlated, implementation in dominant strategies is possible. For highly correlated costs, this is no longer the case.

After substituting the optimal transfers in the regulator's optimization problem and observing that this problem is symmetric in probabilities $Q^I(\underline{\theta},\overline{\theta})$ and $Q^I(\overline{\theta},\underline{\theta})$, we obtain the following optimization problem:

$$\max_{\{Q^I(.)\}} \{Q^I(2\overline{\theta})p^H w^I(\overline{\theta},\overline{\theta}) + Q^I(\underline{\theta}+\overline{\theta})q[w^I(\underline{\theta},\overline{\theta}) + w^I(\overline{\theta},\underline{\theta})] + Q^I(2\underline{\theta})w^I(\underline{\theta},\underline{\theta})\}$$
$$\text{s.t. } 0 \leq Q^I(\theta_1+\theta_2) \leq 1, \text{ for } \theta_1,\theta_2 \in \{\underline{\theta},\overline{\theta}\},$$

where

$$w^I(\widetilde{\theta}) = V - (1+\lambda)(\widetilde{\theta}_1+\widetilde{\theta}_2) - \lambda\frac{\sum_{i=1}^2 \Pr[\theta_i < \widetilde{\theta}_i, \theta_j = \widetilde{\theta}_j]}{\Pr[\theta = \widetilde{\theta}]}(\overline{\theta}-\underline{\theta})$$

is the "virtual welfare" at costs $(\widetilde{\theta}_1,\widetilde{\theta}_2)$ under independent input supply. Due to symmetry $w^I(\underline{\theta},\overline{\theta}) = w^I(\overline{\theta},\underline{\theta})$, which makes $w^I(.)$ a function of total costs only. Given the optimal transfer scheme of independent input supply, incentive constraints do not put any restriction upon the probabilities of production. Under monopolistic input supply the probability scheme was required to be non-increasing in total costs.

It is easy to check that the following proposition holds.

Proposition 2.5 *For IIS the optimal probabilities of production are such that production takes place with certainty whenever the virtual value of welfare is positive:*

$$Q^I(\theta_1+\theta_2) = \begin{cases} 1, \text{ if } w^I(\theta_1+\theta_2) \geq 0 \\ 0, \text{ otherwise} \end{cases}, \text{ for } \theta_1, \theta_2 \in \{\underline{\theta}, \overline{\theta}\}.$$

For small values of q ($q < q^I$, high correlation) monotonicity of $w^I(.)$ breaks down. In that case, the optimal $Q^I(.)$ is no longer monotonous in total production costs. By making $Q^I(\underline{\theta}+\overline{\theta})$ smaller than $Q^I(2\overline{\theta})$ the regulator saves informational rents. Under IIS the regulator chooses a probability of production scheme that is not feasible under MIS. Therefore the choice for IIS enables the regulator to save more rents than under MIS.

The optimal transfer and probability of production schemes differ from those obtained in the substitutable products case studied by Dana (1993). As we noted before, it is not optimal to choose discriminatory probabilities of production when inputs are perfect complements. Because of this, the regulator has to rely more on the transfers to discriminate between input producers. He does this especially when cost correlation becomes high, i.e. $q < q^I$, by shifting all informational rents to the $(\underline{\theta}, \underline{\theta})$ state of nature, which does not happen in Dana (1993).

When the producers have *unlimited* liability and costs are positively correlated, the first-best expected welfare can be implemented, see e.g. Crémer and McLean (1985). This requires a regulatory scheme with large *ex post* punishments and rewards for low degrees of correlation. For firms that are protected by limited liability laws these punishment are not feasible for the regulator. The best he can do then is to choose the scheme of propositions 2.1, 2.3 and 2.5.

2.4 The Optimal Organizational Choice

The propositions in the previous section illustrate the difference between the optimal monopolistic and independent regulatory schemes. In this section we study which scheme yields the higher expected social welfare. The proposition's proof is relegated to the Appendix.

For high values of q (low correlation coefficients) the optimal probabilities of production under both MIS and IIS are non-increasing in the producers' total cost. This means that there are transfer schemes that implement the optimal independent supply probabilities of production, $Q^I(.)$ under MIS. It is easy to show that the expected transfer payment that implements $Q^I(.)$ under MIS, $E_\Theta\{T(\Theta)\}$, is smaller than the expected total transfers under IIS, $E_\theta\{t^1(\theta)+t^2(\theta)\}$. In state $(\underline{\theta}, \underline{\theta})$ the regulator needs to give both independent input suppliers an incentive not to overstate their costs. A monopolistic input supplier with costs $(\underline{\theta}, \underline{\theta})$ must effectively only be induced not to say that he has intermediate cost $\underline{\theta} + \overline{\theta}$. Because the monopolist coordinates his cost messages, he internalizes the externality that a cost overstatement causes on the other input producer. This effect is called the "informational externality" effect.

For low values of q (high correlation coefficients) the incentive constraints for the probabilities of production under MIS become binding. Because the optimal production probabilities under IIS do not obey these monotonicity constraints, they are not feasible for the monopolistic input supply problem. The non-monotonous probability scheme saves informational rents. By conditioning each independent suppliers' informational rents on both suppliers' cost message, the regulator can extract some of their rents. This is called the yardstick competition effect. Due to this effect, independent input supply yields higher expected welfare than monopolistic supply for low q.

The following proposition shows how the optimal organizational structure depends on q. Define the critical values:

$$\overline{q}^1 = \frac{1}{4}\sqrt{p^H}\left[\sqrt{p^H\left(\frac{4}{\lambda}+\frac{1}{\lambda^2}\right)+4} - \sqrt{p^H}\left(\frac{1+2\lambda}{\lambda}\right)\right],\ \overline{q}^2 = \frac{p^H(1-p^H)}{p^H(\frac{1+2\lambda}{\lambda})+1}, \text{ and}$$

$$\overline{v} = \frac{p^H}{p^H-2q}\left[(1+\lambda)2\overline{\theta} + \lambda\frac{2q}{p^H}(\overline{\theta}-\underline{\theta})\right] - \frac{2q}{p^H-2q}\left[(1+\lambda)(\underline{\theta}+\overline{\theta}) + \lambda\frac{p^L}{2q}(\overline{\theta}-\underline{\theta})\right].$$

Proposition 2.6 *The regulator chooses:*
(i) MIS, for $q \geq \max\{\overline{q}^1, \overline{q}^2\}$,
(ii) MIS only if $V < \overline{v}$, *for* $\overline{q}^1 < q < \overline{q}^2$,
(iii) IIS only if $V < \overline{v}$, *for* $\overline{q}^2 < q < \overline{q}^1$,
(iv) IIS, for $q \leq \min\{\overline{q}^1, \overline{q}^2\}$.

Figure 2.1 illustrates regions (i) until (iv) for $\lambda = 1$. Along the horizontal axis we depict p^H, while probability q is along the vertical axis. The dotted line represents critical value $\overline{q}^1$, and the thin line stands for critical value $\overline{q}^2$.

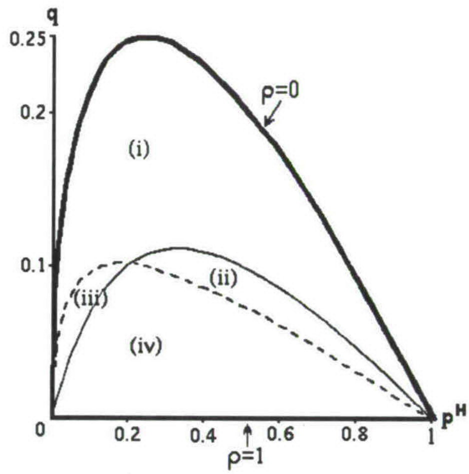

Figure 2.1: Regions (i)-(iv)

The proposition confirms that the regulator prefers IIS for high correlation, while he prefers MIS for low correlation. This is intuitive given the presence of the yardstick competition and informational externality effect.

An alternative interpretation of the proposition is the following. For big enough q the regulator's choice of the industry's organization depends on the firms' liability structure. If firms have unlimited liability, the regulator can punish independent input suppliers severely for unlikely and unfavorable cost combinations, and thereby extract all informational rents. Limited liability puts a binding upper bound to the independent input suppliers' punishments which makes the regulator prefer monopolistic input supply. This means that both the cost correlation and the producers' liability structure influence the optimal organizational structure of complementary input supply.

2.5 Conclusion

In this chapter we showed that the optimal organizational structure of regulating complementary input supply trades off two effects. The yardstick competition effect occurs when costs are correlated. A multi-product monopolist can coordinate the reports that he sends to the regulator. Independent firms, however, send reports independently. The regulator can extract some of the independent firms rents by comparing the firms' reports and rewarding or punishing firms on the basis of this comparison. The second effect is the informational externality effect, and is most powerful when costs are independently distributed. Because independent firms send reports independently, they do not internalize the externality that their reports has on the other firm's payoff. The regulator must therefore give both firms an incentive to not overstate their costs. A monopolistic input supplier internalizes this externality, and this saves rents for the regulator. The yardstick competition is strongest when costs are highly correlated. When costs are independent, the yardstick competition effect disappears. This implies that complementary activities with highly correlated costs are best regulated by creating two separate firms each performing one activity only. In contrast, complementary activities with low cost correlation are best regulated by having one firm that performs both activities.

Not only cost correlation, but also the liability structure of input producers matters, when costs have a small, non-negative correlation coefficient. For small, non-negative correlation coefficients, a social welfare maximizing regulator prefers monopolistic input supply when the producers are protected by limited liability, while he prefers duopolistic input supply under unlimited liability. Under unlimited liability and positive cost correlation, the regulator extracts all the independent suppliers' rents by punishing an input supplier severely in unfavorable and unlikely states of nature and rewarding them in other states. Limited liability makes these punishments infeasible, since producers must receive non-negative profits in all states of nature. Therefore, in industries consisting of suppliers with limited liability the yardstick competition effect is weaker than in industries with unlimitedly liable firms. Higher correlation coefficients make independent input supply more desirable for the welfare optimizing regulator under both limited and unlimited liability.

The regulatory schemes that implement the optimal expected welfare level in our model are quite different compared to that in Dana (1993), where goods are divisible substitutes.

In our model the choice between monopolistic and independent input supply is made before costs are reported, and are therefore, in a sense, exogenous. Endogenizing the organizational choice of the regulator by procuring the control over input production between two bidders could give interesting new insights in the current problem.

It could also be worthwhile to investigate the implications of this chapter's insights for the problem of access pricing. In the problem of access pricing a monopolistic firm supplies both a bottleneck facility and a final good that makes use of this facility. There are also other final goods suppliers that need the bottleneck facility. In comparison with this chapter, the monopolistic firm's incentives to report costs truthfully are distorted, because his cost messages affect competition in the final goods market. If the regulator separates the facility provider from the final good producer, this distortion vanishes. This would save informational rents. However, separation triggers the informational externality effect, which costs the regulator rents. Whether or not separation of the monopolist is socially desirable, needs to be explored.

2.6 Appendix

The first subsection of this Appendix contains the proof to lemmas 2.1, 2.2 and 2.3, which concern optimal monopolistic input supply schemes. The second subsection gives the proof to propositions 2.1, 2.3 and 2.5, and to 2.2 and 2.4, which concerns the optimal regulatory schemes under independent input supply. The last subsection of this Appendix proves proposition 2.6, which concerns the optimal organization of input supply.

2.6.1 MIS: Proof of Lemmas 2.1, 2.2 and 2.3

Note that the welfare optimization problem under MIS is a linear programming problem. Suppose that the $2\overline{\theta}$-monopolist's participation constraint is binding with slack variable $\hat{s}^h = \lambda$, where λ is the social cost of public funds. This gives transfer $T(2\overline{\theta})$ in lemma 2.1. Take the incentive compatibility constraint of a $(\underline{\theta}+\overline{\theta})$-monopolist overstating his cost binding, and set its slack variable $\hat{s}^{H|m} = \lambda(1-p^H)$. This results in transfer $T(\underline{\theta}+\overline{\theta})$. Take the incentive compatibility constraint for a $2\underline{\theta}$-monopolist claiming to be $(\underline{\theta}+\overline{\theta})$ binding with slack variable $\hat{s}^{m|L} = \lambda p^L$. This determines transfer $T(2\underline{\theta})$ of lemma 2.1. Finally we suppose that neither the incentive constraints for understating costs are never binding, nor the participation constraints for low and middle total costs are binding. We can write down the following reduced dual problem for the remaining slack variables s_Q^L, s_Q^m, s_Q^H of the probability feasibility constraints, $Q^M(.) \leq 1$, and the incentive compatibility constraint of a $2\underline{\theta}$-cost monopolist claiming to have total costs $2\overline{\theta}$, $s^{H|L}$:

$$\min_{s\geq 0} \left\{ s_Q^L + s_Q^m + s_Q^H \right\}$$
$$\text{s.t.} \begin{cases} s_Q^L \geq p^L[V-(1+\lambda)2\underline{\theta}] \\ s_Q^m - (\overline{\theta}-\underline{\theta})s^{H|L} \geq 2q[V-(1+\lambda)(\underline{\theta}+\overline{\theta}) - \lambda\frac{p^L}{q}(\overline{\theta}-\underline{\theta})] \\ s_Q^H + (\overline{\theta}-\underline{\theta})s^{H|L} \geq p^H[V-(1+\lambda)2\overline{\theta} - \lambda\frac{1-p^H}{p^H}(\overline{\theta}-\underline{\theta})] \end{cases}$$

for $s_Q^L, s_Q^m, s_Q^H, s^{H|L} \geq 0$.

For $q \geq q^M$ we set $\hat{s}^{H|L} = 0$, which gives dual solution:

$$\begin{aligned}\hat{s}_Q^L &= \max\{0, p^L w^M(2\underline{\theta})\}\\ \hat{s}_Q^m &= \max\{0, 2qw^M(\underline{\theta}+\overline{\theta})\}\\ \hat{s}_Q^H &= \max\{0, p^H w^M(2\overline{\theta})\}.\end{aligned}$$

Then the primal solution of lemmas 2.1 and 2.2 is feasible, since it satisfies the complementary slackness conditions. And it implements the optimal dual value $\hat{s}_Q^L + \hat{s}_Q^m + \hat{s}_Q^H$. From the duality theorem we can conclude that this scheme is optimal.

For $q < q^M$ we take $\hat{s}^{H|L} > 0$. This implies from the complementary slackness conditions that $Q^M(2\overline{\theta}) = Q^M(\underline{\theta}+\overline{\theta})$. Then the following slack variables solve the reduced dual problem:

$$\begin{aligned}\hat{s}_Q^L &= \max\{0, p^L w^M(2\underline{\theta})\}\\ \hat{s}_Q^m + \hat{s}_Q^H &= \max\{0, 2qw^M(\underline{\theta}+\overline{\theta}) + p^H w^M(2\overline{\theta})\}.\end{aligned}$$

Then the scheme of lemmas 2.1 and 2.3 is feasible, since it satisfies the complementary slackness conditions. And it implements $\hat{s}_Q^L + \hat{s}_Q^m + \hat{s}_Q^H$. It follows from the duality theorem that this scheme is optimal.

This completes the proof of lemmas 2.1, 2.2 and 2.3.

2.6.2 IIS: Proofs

Optimal Schemes: Proof of Propositions 2.1, 2.3 and 2.5

Under IIS, the welfare optimization problem is a linear programming problem. Observe that the schemes under propositions 2.5 and proposition 2.1 or 2.3 give feasible variables to this problem. Make firms' incentive compatibility constraint for overstating costs binding, and set the slack variable $\hat{s}_i^{H|L} = \lambda$. Also make the high-cost firms' participation constraint binding by choosing slack variables $\hat{s}_1^{HL} = \lambda(p^L + q)$ and $\hat{s}_1^{HH} = \lambda(q + p^H)$, and similar slack variables for firm 2. Set all remaining slack variables for incentive compatibility and participation constraints equal to 0. Choose the slack variables for the feasibility of probability of production as follows:

$$\begin{aligned}s_Q^{LL} &= \max\{0, p^L[V - (1+\lambda)2\underline{\theta}]\}\\ s_Q^{HL} = s_Q^{LH} &= \max\left\{0, q[V - (1+\lambda)(\underline{\theta}+\overline{\theta}) - \lambda\frac{p^L}{q}(\overline{\theta}-\underline{\theta})]\right\}\\ s_Q^{HH} &= \max\left\{0, p^H[V - (1+\lambda)2\overline{\theta} - \lambda\frac{2q}{p^H}(\overline{\theta}-\underline{\theta})]\right\}.\end{aligned}$$

Consequently, for $q \geq q^I$ the regulatory scheme from propositions 2.1 and 2.5 satisfies the complementary slackness condition and equalizes the primal and dual values. Therefore this scheme is optimal. For $q < q^I$ the regulatory scheme from propositions 2.3 and 2.5 satisfies the complementary slackness condition and it equalizes dual and primal values. It follows from the duality theorem that the regulatory schemes are optimal. This completes the proof to propositions 2.1, 2.3 and 2.5.

Dominant Strategy Equilibrium: Proofs of Propositions 2.2 and 2.4

Suppose that producer 2 chooses mixed strategy $p_2(\theta_2) = \Pr(\widetilde{\theta} = \underline{\theta}|\theta_2)$ in the message sending stage. Given this strategy, producer 1 assigns the following probability to a low cost message:

$$\Pr(\widetilde{\theta}_2 = \underline{\theta}|\theta_1, p_2(.)) = \Pr(\theta_2 = \underline{\theta}|\theta_1)p_2(\underline{\theta}) + \Pr(\theta_2 = \overline{\theta}|\theta_1)p_2(\overline{\theta}).$$

The expected profit for producer 1 from stating low costs is:

$$\begin{aligned}
&E_{\theta_2}\{\pi_1(p_1(\theta_1) = 1, p_2(\theta_2)|\theta_1)\} = \\
&\Pr(\widetilde{\theta}_2 = \underline{\theta}|\theta_1, p_2)\left[t^1(\underline{\theta},\underline{\theta}) - \underline{\theta}Q^I(\underline{\theta},\underline{\theta})\right] + \\
&+\left(1 - \Pr(\widetilde{\theta}_2 = \underline{\theta}|\theta_1, p_2)\right)\left[t^1(\underline{\theta},\overline{\theta}) - \underline{\theta}Q^I(\underline{\theta},\overline{\theta})\right],
\end{aligned}$$

and he obtains the following from stating high costs:

$$\begin{aligned}
&E_{\theta_2}\{\pi_1(p_1(\theta_1) = 0, p_2(\theta_2)|\theta_1)\} = \\
&\Pr(\widetilde{\theta}_2 = \underline{\theta}|\theta_1, p_2)\left[t^1(\overline{\theta},\underline{\theta}) - \underline{\theta}Q^I(\overline{\theta},\underline{\theta})\right] + \\
&+\left(1 - \Pr(\widetilde{\theta}_2 = \underline{\theta}|\theta_1, p_2)\right)\left[t^1(\overline{\theta},\overline{\theta}) - \underline{\theta}Q^I(\overline{\theta},\overline{\theta})\right].
\end{aligned}$$

Substituting the modified regulatory transfer scheme from proposition 2.2 into the expected profit functions proves this proposition immediately.

The proof to proposition 2.4 is given in the remainder of this subsection. A Bayesian equilibrium in interim dominant strategies cannot be obtained for arbitrary small changes to proposition 2.3's transfer scheme and the optimal probabilities of production. If one producer always states high costs, i.e. $p_i(\theta_i) = 0$ for all $\theta_i \in \{\underline{\theta}, \overline{\theta}\}$, the other producer has a strict preference to overstate his cost, whenever $Q^I(\overline{\theta},\overline{\theta}) > 0$. This proves proposition 2.4.

2.6.3 MIS vs IIS: Proof of Proposition 2.6

In this subsection we compare the expected optimal welfare level under MIS with that under IIS. Define $\Delta\theta = \overline{\theta} - \underline{\theta}$ and $\Delta W = E_\theta\{W^I(\theta)\} - E_\Theta\{W^M(\Theta)\}$.

We first show how the critical values are ordered. It is obvious that $q^M \leq \overline{q}^2$. Furthermore, $q^M \leq \overline{q}^1$, because this gives:

$$\frac{\sqrt{p^H}\left[(p^H+\lambda(1+p^H))\sqrt{4\lambda^2+p^H(4\lambda+1)}-\sqrt{p^H}(4\lambda^2+\lambda+(3\lambda+1)p^H)\right]}{4\lambda(p^H+\lambda(1+p^H))} \geq 0,$$

which is equivalent to:

$$(p^H+\lambda(1+p^H))^2(4\lambda^2+p^H(4\lambda+1)) \geq p^H(4\lambda^2+\lambda+(3\lambda+1)p^H)^2,$$

and this is equivalent to $4\lambda^3(1-p^H)^2(\lambda+p^H) \geq 0$, which obviously holds always.

The inequality $\overline{q}^2 \leq q^I$ always holds, because it gives:

$$(p^H+\lambda(1+2p^H))\sqrt{\lambda^2(p^H+8)+p^H(6\lambda+1)} \geq \sqrt{p^H}(\lambda^2(7+2p^H)+\lambda+(5\lambda+1)p^H),$$

which is equivalent to $8\lambda^3(1-p^H)^2(\lambda+p^H)^2 \geq 0$, which obviously holds always.

For later use we prove the following lemma.

Lemma 2.4 $\overline{q}^1 \geq \overline{q}^2 \Leftrightarrow p^H \leq 2q$.

Proof. Take $p^H = \frac{\delta\lambda}{4\lambda+1}$, with $0 \leq \delta \leq 4+\frac{1}{\lambda}$. Then:

$$\overline{q}^1-\overline{q}^2 = \frac{(1+4\lambda+\delta(1+2\lambda))\sqrt{\frac{\delta(4\lambda+\delta)}{4\lambda+1}}-\delta(1+6\lambda+\delta)}{4(1+4\lambda+\delta(1+2\lambda))}.$$

Therefore, $\overline{q}^1 \geq \overline{q}^2$ is equivalent to:

$$\delta(1+4\lambda+\delta(1+2\lambda))^2(4\lambda+\delta) \geq \delta^2(1+6\lambda+\delta)^2(4\lambda+1),$$

which gives:

$$4\delta\lambda(1-\delta)(1+(4-\delta)\lambda)(1+\delta+4\lambda) \geq 0.$$

This holds whenever $\delta \leq 1$. Finally, note that for $\delta = 1$ we obtain $\overline{q}^1 = \overline{q}^2 = \frac{\delta\lambda}{2(4\lambda+1)} = \frac{1}{2}p^H$, which proves the lemma.□

Note that for $Q^M(2\underline{\theta}) = Q^M(\underline{\theta}+\overline{\theta}) = 0, Q^M(2\overline{\theta}) = 1$, and $Q^I(2\underline{\theta}) = 1, Q^I(\underline{\theta}+\overline{\theta}) = 0, Q^I(2\overline{\theta}) = 1$ we have:

$$\Delta W = p^H\left(V-(1+\lambda)2\overline{\theta}-\lambda\frac{2q}{p^H}\Delta\theta\right)-2q\left(V-(1+\lambda)(\underline{\theta}+\overline{\theta})-\lambda\frac{p^L}{2q}\Delta\theta\right). \quad (2.5)$$

For $q \leq q^M$ and $q \geq q^I$ the expected welfare comparison is straightforward, resulting in a preference for independent and monopolistic input supply, respectively. For $q^M < q < q^I$ we distinguish four cases, that are analyzed in the following four cases.
(i) For $\max\{\overline{q}^1, \overline{q}^2\} \leq q \leq q^I$ we have the following parameter ordering:

$$\begin{aligned}(1+\lambda)(\underline{\theta}+\overline{\theta})+\lambda\frac{p^L}{2q}\Delta\theta &< (1+\lambda)2\overline{\theta}+\lambda\frac{2q}{p^H}\Delta\theta < \\ &< (1+\lambda)(\underline{\theta}+\overline{\theta})+\lambda\frac{p^L}{q}\Delta\theta \leq (1+\lambda)2\overline{\theta}+\lambda\frac{1-p^H}{p^H}\Delta\theta.\end{aligned} \tag{2.6}$$

The welfare comparison is straightforward, except for the case in which:

$$(1+\lambda)2\overline{\theta}+\lambda\frac{2q}{p^H}\Delta\theta < V < (1+\lambda)(\underline{\theta}+\overline{\theta})+\lambda\frac{p^L}{q}\Delta\theta. \tag{2.7}$$

Then ΔW is as in (2.5). This means that for $p^H > 2q$, $\Delta W < 0 \Leftrightarrow V < \overline{v} \Leftrightarrow$

$$\begin{aligned}V &< (1+\lambda)(\underline{\theta}+\overline{\theta})+\lambda\frac{p^L}{q}\Delta\theta+ \\ &+\frac{p^H}{p^H-2q}\left([(1+\lambda)2\overline{\theta}+\lambda\frac{1-p^H}{p^H}\Delta\theta]-[(1+\lambda)(\underline{\theta}+\overline{\theta})+\lambda\frac{p^L}{q}\Delta\theta]\right)\end{aligned}$$

which holds given (2.6) and (2.7). For $p^H = 2q$, $\Delta W < 0$ is a direct consequence of (2.6). Finally, for $p^H < 2q$, $\Delta W < 0 \Leftrightarrow V > \overline{v} \Leftrightarrow$

$$\begin{aligned}V &> (1+\lambda)2\overline{\theta}+\lambda\frac{2q}{p^H}\Delta\theta+ \\ &+\frac{2q}{p^H-2q}\left([(1+\lambda)2\overline{\theta}+\lambda\frac{2q}{p^H}\Delta\theta]-[(1+\lambda)(\underline{\theta}+\overline{\theta})+\lambda\frac{p^L}{2q}\Delta\theta]\right)\end{aligned}$$

which holds given (2.6) and (2.7).
(ii) Due to the lemma 2.4, $\overline{q}^1 < q < \overline{q}^2$ gives $p^H > 2q$, and:

$$\begin{aligned}(1+\lambda)(\underline{\theta}+\overline{\theta})+\lambda\frac{p^L}{2q}\Delta\theta &< (1+\lambda)2\overline{\theta}+\lambda\frac{2q}{p^H}\Delta\theta < \\ &< (1+\lambda)2\overline{\theta}+\lambda\frac{1-p^H}{p^H}\Delta\theta < (1+\lambda)(\underline{\theta}+\overline{\theta})+\lambda\frac{p^L}{q}\Delta\theta.\end{aligned} \tag{2.8}$$

The welfare comparison is straightforward, except for:

$$(1+\lambda)2\overline{\theta}+\lambda\frac{2q}{p^H}\Delta\theta < V < (1+\lambda)2\overline{\theta}+\lambda\frac{1-p^H}{p^H}\Delta\theta.$$

Then ΔW is as in (2.5), and $\Delta W > 0$ whenever $V > \overline{v}$. It suffices to note that, due to (2.8),

$$(1+\lambda)2\overline{\theta} + \lambda\frac{2q}{p^H}\Delta\theta < \overline{v} < (1+\lambda)2\overline{\theta} + \lambda\frac{1-p^H}{p^H}\Delta\theta,$$

since rewriting gives:

$$\begin{aligned}\overline{v} &= (1+\lambda)2\overline{\theta} + \lambda\frac{2q}{p^H}\Delta\theta + \\ &\quad -\frac{2q}{p^H-2q}\left([(1+\lambda)(\underline{\theta}+\overline{\theta}) + \lambda\frac{p^L}{2q}\Delta\theta] - [(1+\lambda)2\overline{\theta} + \lambda\frac{2q}{p^H}\Delta\theta]\right),\end{aligned}$$

and

$$\begin{aligned}\overline{v} &= (1+\lambda)2\overline{\theta} + \lambda\frac{2q}{p^H}\Delta\theta + \\ &\quad -\frac{2q}{p^H-2q}\left([(1+\lambda)(\underline{\theta}+\overline{\theta}) + \lambda\frac{p^L}{q}\Delta\theta] - [(1+\lambda)2\overline{\theta} + \lambda\frac{1-p^H}{p^H}\Delta\theta]\right).\end{aligned}$$

(iii) From lemma 2.4, $\overline{q}^2 < q < \overline{q}^1$ implies that $p^H < 2q$, and:

$$\begin{aligned}(1+\lambda)2\overline{\theta} + \lambda\frac{2q}{p^H}\Delta\theta &< (1+\lambda)(\underline{\theta}+\overline{\theta}) + \lambda\frac{p^L}{2q}\Delta\theta < \\ &< (1+\lambda)(\underline{\theta}+\overline{\theta}) + \lambda\frac{p^L}{q}\Delta\theta < (1+\lambda)2\overline{\theta} + \lambda\frac{1-p^H}{p^H}\Delta\theta.\end{aligned} \tag{2.9}$$

For this case the welfare is straightforward except for:

$$(1+\lambda)(\underline{\theta}+\overline{\theta}) + \lambda\frac{p^L}{2q}\Delta\theta < V < (1+\lambda)(\underline{\theta}+\overline{\theta}) + \lambda\frac{p^L}{q}\Delta\theta.$$

Then ΔW is as in (2.5), and $\Delta W > 0$ whenever $V < \overline{v}$. Again it suffices to note that, due to (2.9),

$$(1+\lambda)(\underline{\theta}+\overline{\theta}) + \lambda\frac{p^L}{2q}\Delta\theta < \overline{v} < (1+\lambda)(\underline{\theta}+\overline{\theta}) + \lambda\frac{p^L}{q}\Delta\theta,$$

since rewriting gives:

$$\begin{aligned}\overline{v} &= (1+\lambda)(\underline{\theta}+\overline{\theta}) + \lambda\frac{p^L}{2q}\Delta\theta + \\ &\quad -\frac{p^H}{p^H-2q}\left([(1+\lambda)(\underline{\theta}+\overline{\theta}) + \lambda\frac{p^L}{2q}\Delta\theta] - [(1+\lambda)2\overline{\theta} + \lambda\frac{2q}{p^H}\Delta\theta]\right),\end{aligned}$$

and

$$\begin{aligned}
\overline{v} &= (1+\lambda)(\underline{\theta}+\overline{\theta}) + \lambda\frac{p^L}{q}\Delta\theta + \\
&-\frac{p^H}{p^H-2q}\left([(1+\lambda)(\underline{\theta}+\overline{\theta}) + \lambda\frac{p^L}{q}\Delta\theta] - [(1+\lambda)2\overline{\theta} + \lambda\frac{1-p^H}{p^H}\Delta\theta]\right).
\end{aligned}$$

(iv) Finally, for $q^M < q \leq \min\{\overline{q}^1, \overline{q}^2\}$ the parameters are ordered as follows:

$$\begin{aligned}
(1+\lambda)2\overline{\theta} + \lambda\frac{2q}{p^H}\Delta\theta &< (1+\lambda)(\underline{\theta}+\overline{\theta}) + \lambda\frac{p^L}{2q}\Delta\theta < \\
&< (1+\lambda)2\overline{\theta} + \lambda\frac{1-p^H}{p^H}\Delta\theta < (1+\lambda)(\underline{\theta}+\overline{\theta}) + \lambda\frac{p^L}{q}\Delta\theta.
\end{aligned} \tag{2.10}$$

The welfare is not straightforward for the case in which:

$$(1+\lambda)(\underline{\theta}+\overline{\theta}) + \lambda\frac{p^L}{2q}\Delta\theta < V < (1+\lambda)2\overline{\theta} + \lambda\frac{1-p^H}{p^H}\Delta\theta. \tag{2.11}$$

This means that for $p^H > 2q$, $\Delta W > 0$ is equivalent to:

$$\begin{aligned}
V &> (1+\lambda)(\underline{\theta}+\overline{\theta}) + \lambda\frac{p^L}{2q}\Delta\theta + \\
&+\frac{p^H}{p^H-2q}\left([(1+\lambda)2\overline{\theta} + \lambda\frac{2q}{p^H}\Delta\theta] - [(1+\lambda)(\underline{\theta}+\overline{\theta}) + \lambda\frac{p^L}{2q}\Delta\theta]\right)
\end{aligned}$$

which holds given (2.10) and (2.11). For $p^H = 2q$, $\Delta W > 0$ is a direct consequence of (2.10). And, finally, for $p^H < 2q$, $\Delta W > 0$ is equivalent to:

$$\begin{aligned}
V &< (1+\lambda)2\overline{\theta} + \lambda\frac{1-p^H}{p^H}\Delta\theta + \\
&+\frac{2q}{p^H-2q}\left([(1+\lambda)2\overline{\theta} + \lambda\frac{1-p^H}{p^H}\Delta\theta] - [(1+\lambda)(\underline{\theta}+\overline{\theta}) + \lambda\frac{p^L}{q}\Delta\theta]\right)
\end{aligned}$$

This completes the proof of proposition 2.6.

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Part II

R&D Races with Learning Laboratories

Introduction to Part II

In this part of the thesis we analyze problems of dynamic competition in research and development (R&D). A special feature of the problems is that innovating firms learn while they invest in R&D. The interaction between firms' incentives to learn, communicate and to develop their innovation is studied for different settings. Firms learn about their costs of development by investing in research. Research investments give information about development costs. After learning, firms decide what information to reveal. Two effects of information revelation are central to the analysis. First, a firm's revelation has a strategic effect. It provides its rival with information about the firm's relative cost efficiency in development. When a firm is expected to be a more efficient investor in development, this discourages its rival's development investments. This effect would therefore give firms an incentive to bias their revelation towards revealing only good news about themselves. The second effect is an informational effect, and conflicts with the strategic effect. When costs of development investments are positively correlated, a firm's revelation does not only reveal something about this firm's costs of investment. A firm also learns something about his own cost of investment from his rival's revelation. This gives firms an incentive to only reveal bad news to their rival. Bad news makes rivals pessimistic about their development costs, and discourages development investments. The interaction between these two conflicting effects determines firms' incentives to acquire, reveal and further build upon information.

In the first chapter we consider an R&D race in which firms always learn about costs of development investments, although learning is imperfect. Therefore it is known that a firm is informed. Firms only do not know what information their rival possesses. Project's costs of development are perfectly correlated, and therefore the informational effect dominates. When firms share revenues this effect is countervailed by free-rider incentives. The relative strength of the two effects determines firm's incentives to invest and reveal information. The verifiability of firms' private information is crucial in determining how much information can and will be revealed between firms. Unverifiable information can never be revealed credibly, while verifiable information results in unraveling for extreme revenue shares only.

In the second chapter of this part of the thesis we analyze an R&D race in which firms learn differently. When a firm learns, it learns perfectly, but whether it learns is uncertain and depends on its research investments. When the acquired information is verifiable, firms face the choice between disclosure and claiming to be uninformed. The second chapter of Part II studies the effects of disclosure regulation on firms' incentives to invest in research and development. Furthermore we investigate the effects of correlation between development costs on firms' incentives to disclose information and to invest. When information is perfectly correlated the informational effect dominates, and firms disclose only bad news. Bad news makes a rival more pessimistic about his costs of development, and consequently discourages those investments. For independently distributed costs the informational effect disappears and the strategic effect rules. Therefore firms disclose their information only when they are efficient development investors, and firms invest aggressively in both research and development.

Chapter 3

Strategic Revelation and Revenue Sharing

3.1 Introduction

Innovative activity has at least three basic properties. It is mostly done in a competitive environment. Firms compete to get an innovation first. Second, it is a dynamic activity. Research and Development (R&D) is a process for which we can distinguish several stages, at least there is a research stage, resulting in a raw prototype, and a development stage in which the prototype is transformed into a final product. Finally R&D is an uncertain activity. Not only is it uncertain when an innovation is going to occur, but also firms could be uncertain about the complexity of the project that they start working on. Only in the course of doing research firms learn whether their project is worthwhile proceeding. For marginal product improvements learning effects can be ignored. But for more fundamental innovations and more experimental research these effects cannot be ignored. The fact that firms learn during the race, and the fact that they could learn from each other, creates new and interesting incentives to invest in R&D. This paper analyzes these incentives. Our analysis consists of three parts. First, we investigate how the fact that firms learn affects their incentives to invest in R&D. Second, we study how these incentives are affected under different regimes of appropriability of the innovation. And, finally, we analyze under what conditions firms will and will not learn from each other in equilibrium.

The simplest situation that captures the competitive, dynamic and informational aspects of innovative activity is the following. Two firms compete over two stages to get an innovation. In the first stage firms obtain an intermediate discovery, and learn about their R&D project. In the second stage firms decide how much to invest in developing the intermediate innovation, given the information acquired in stage 1. Firms compete to get the developed final product first. An early intermediate discovery in an R&D race can have two opposite effects on competition. We distinguish a strategic and an informational effect, and discuss them in the next two paragraphs.

In most literature on dynamic R&D competition the progress of one firm in their project discourages its rivals to invest in the innovation. Taking a lead in the race gives the leading firm a strategic advantage, e.g. see Grossman and Shapiro (1987), and Harris and Vickers (1987). This is a "strategic effect". If firms could credibly signal that they made an early intermediate discovery without revealing the contents of this discovery, they would always do so. The problem is that this revelation cannot happen credibly unless the contents of the discovery are revealed also. But revealing the contents of the discovery enables rivals to catch up in the race, which encourages further investments. Therefore a leading firm is only willing to obtain and reveal information about its progress in the race if it is sufficiently compensated for doing so. Compensation can happen by means of a licencing arrangement or an intermediate patent (see, e.g., Chang (1995), Green and Scotchmer (1995), Scotchmer and Green (1990) and Kabla (1997)) or grace period (see Goyal and De Laat, 1998). Thus there is a trade-off between the incentive to reveal information and leaving the informed firm an advantage in the race. The literature mostly focuses on this trade-off in R&D races.

For fundamental innovations[1] we see an effect that is opposite to the strategic effect. After an early intermediate success by one firm, rivals flock in and invest to obtain the final innovation first. This effect could be explained in the following setting, as in Choi (1991). Firms learn about the properties of the project while they work on it. These properties are universal for the industry. Favorable information for one firm is favorable also for its rivals. Then progressing in the race and disclosing this progress makes all firms more optimistic, and more willing to invest. This is an "informational effect". But when favorable information for one firm also encourages rivals to invest in the project, the firm might want to prevent its rivals from learning this information. There might be an incentive not to reveal any good news that firms learned.

The strategic effect gives firms an incentive to state that they made early intermediate discoveries, while they would keep intermediate successes secret under the

[1] A classic example of this kind of innovation would be the 1986 breakthrough in cold superconductivity. For a description of the breakthrough by IBM, and its resulting race for even colder superconductivity, see Choi (1991).

informational effect. In practice these two effects interact, and this interaction determines the firms' incentives to invest in both stages of the race. In this chapter we separate the acquisition of information from the acquisition of a leading position in the race. First, firms invest solely in acquiring information, and then invest in winning the race. Furthermore, we maximize the scope for firms to learn from their rival by assuming perfect positive correlation between the firms' projects. We thereby focus on the informational effect of intermediate discoveries and its subsequent problems of information revelation. This gives a sharper trade-off between incentives to reveal and acquire information.

This chapter contributes in two important ways to the study of the trade-off between the infomational and strategic effect. First, we study the effects of appropriability of revenues on the firms' incentives to invest in R&D. Most literature on R&D races focuses on the winner-takes-all race. This is, however, an extreme setting that needs not be realistic. We add more realism to the economic analysis by studying settings in which the winner does not take all. In particular, we assume that firms share a fixed portion of their revenues. Revenue sharing introduces free-rider effects to the analysis. These free-rider effects interact in an interesting way with the informational and strategic effects.

The second main contribution of this chapter is to endogenize firms' information. Information is endogenized in two directions. First, each firm invests in costly information acquisition. The incentives to invest depend on the appropriability of both the acquired information, and the innovation's revenues. When the acquired information is public, firms have a low incentive to invest in information acquisition, because they prefer to free ride on their rival's information acquisition investments. And when only part of the revenues from innovation are appropriated by a firm, both negative as well as positive externalities on research incentives exist between firms. The negative effect is due to the erosion of expected revenues from a firm's own information acquisition investments. This is a free-rider effect. The positive externality of revenue sharing is active when the firms' acquired information is public. The externality is caused by the fact that the information generated by one firm affects beliefs and consequently expected revenues of the firm's rival. Since part of these revenues spill over, firms have a bigger incentive to invest in information acquisition.

The second reason why the firms' information is endogenous is because firms can choose what information they reveal. That is, the revelation of information is not exogenous, but a strategic choice of the firms. When information is non-verifiable, firms never completely reveal their information, while there is an equilibrium in which they completely conceal information. This result holds for any way in which firms share revenues. These results are reversed for extreme revenue shares, however, when information is verifiable. Firms cannot credibly conceal any verifiable information, and will therefore fully disclose. For intermediate revenue shares there is no equilibrium in which firms completely reveal their information.

These two main contributions of the chapter are discussed in more detail in the next sections.

Related literature: Papers by Hendricks and Kovenock (1989), Choi (1991), Malueg and Tsutsui (1997), and Cyert and Kumar (1996) study models in which firms learn about their project's characteristics while they invest in it. In their models the information obtained from research is publicly observable. Firms learn from each other's experience without cost. Information is incomplete, but symmetric. We show in this chapter that firms have incentives to misrepresent their intermediate research results to affect competition in the development stage. Furthermore, we analyze how investments are affected by revenue sharing, and how they compare to the industry's efficient investments. We show that firms' expected profits can be increased by relaxing the "winner-takes-all" assumption.

Dewatripont *et al.* (1999) give sufficient conditions under which a manager's incentives for information acquisition investments are affected by an additional signal about his project. We perform a similar exercise for signals that are generated by a firm's rival. We extend the analysis by introducing competition both in information acquisition, as well as in the determination of firms' revenue.

Problems of strategic information revelation in R&D races are studied by Bhattacharya *et al.* (1990, 1992) and d'Aspremont *et al.* (1996, 1998) but in their models information is exogenous (and partly verifiable). Another model of endogenous information spillovers between competing firms is analyzed by Katsoulacos and Ulph (1998), and Ulph and Katsoulacos (1998). Their problem deals with information about the contents of the intermediate innovation, and not information about the costs of proceeding with the project. This puts more emphasis on the strategic effect of information revelation.

The effects for incentives of racing firms after the relaxation of the "winner-takes-all" patent scheme are studied in La Manna *et al.* (1989) and Denicolò (1996). In these papers the social optimality of full-scope patents is seriously questioned. We perform a similar exercise, but in an environment in which firms learn.

Problems in which information revelation occurs between competitors are problems of information sharing in oligopoly.[2] Novshek and Sonnenschein (1982), Fried (1984), and Creane (1995) study models in which firms acquire and reveal information before they compete.[3] However, in these models firms can commit *ex ante* whether to reveal information or not. This is a strong assumption that need not always be realistic. In fact, Ziv (1993) shows that the scope for information sharing is drastically reduced when firms cannot commit *ex ante* and information is non-verifiable. We follow the same modelling approach as in the paper by Ziv.

The chapter is organized as follows. In the next section we describe the basic model. In section 3 the efficient investments that maximize total industry's profits are characterized. These investments serve as a benchmark. Section 4 analyzes the effects of introducing competition in this setting, while signals remain public information. This gives the equilibrium investments of competing firms that receive publicly observable signals about the project's complexity. In section 5 we analyze the equilibrium investments when firms have only private signals. The sixth section discusses what information is revealed, and what investments are chosen, when firms reveal information strategically. Section 7 discusses the assumptions on observability of research investments, and the last section concludes. All proofs are relegated to the Appendix.

3.2 The Model

We consider an industry in which two firms compete over two stages to obtain an innovation. Firms work on the same innovation but compete to get it first. Since firms work on the same innovation, we assume that their costs of investments are perfectly positively correlated. In the first stage firms acquire information about the costs of development investments, that should lead to the innovation. This is the research stage. In the second stage the firms actually try to develop the innovation. We call this stage the development stage. The firm that develops the innovation first, the winner, receives prize W. When both firms develop the innovation, each firm receives prize T. Naturally, we assume that $0 \leq T \leq \frac{1}{2}W$. At one extreme firms

[2]For a survey of the main results of information sharing in oligopoly, see Gal-Or (1986) and Raith (1996).

[3]Other papers, e.g. see Li *et al.* (1987), Hwang (1993, 1995) and Hauk and Hurkens (1998), study the incentives of competing firms to acquire information given that the acquired information remains private.

share the revenues from innovation equally, while at the other extreme, firms compete fiercely in the product market which leaves no rents for either of them. A firm that does not develop the innovation successfully receives no revenues. Define $\Delta \equiv W - T$ as the difference between the prizes of winning and tying. Note that our assumption on T implies that $\frac{1}{2}W \leq \Delta \leq W$.

At the beginning of the race firms do not know the complexity of the project they work on. Complexity directly affects the cost of investments in developing the innovation, and is summarized by the parameter θ. The project can either be easy, $\theta = \underline{\theta}$, or difficult, $\theta = \overline{\theta}$, to complete, with $0 < \underline{\theta} < \overline{\theta}$. When the project is easy (resp. difficult), it is easy (resp. difficult) for both firms. An easy project has low marginal cost of development. A difficult project is completed at high marginal cost. The probability of an easy (resp. difficult) project is p (resp. $1 - p$), with $0 < p < 1$.

In the research stage firms find a prototype, and learn about the costs of development investment. Firm i does research by making an investment $R_i \in [0, 1]$. Research investments are not observable. Firm i expects research investment r_j from its rival firm j. Costs of research investments are quadratic in investments, $C(R_i) = \frac{\rho}{2} R_i^2$, with ρ high enough such that coordinating firms both invest in research. Learning is, however, not perfect. After firms invest in research they receive a signal about the project's complexity. The quality of the signal depends on the investments in research. When the project is difficult, investments always lead to a bad signal, $t_i = \overline{t}$, for $i = 1, 2$. For an easy project firm i's signal depends on its research investment, R_i. Firm i receives a good signal, $t_i = \underline{t}$, with probability R_i, while the probability of a bad signal, $t_i = \overline{t}$, is $1 - R_i$, with $i = 1, 2$. Signals are independently distributed between firms given the project's complexity. The first-stage stochastic structure for firm i is depicted in Figure 3.1 below. The dashed lines represent firm i's information sets.

We make different assumptions about the nature of the firms' signals. In the following two sections we assume that signals are public information, while in section 5 we assume that signals are private information to firms. Besides the fact that these cases are interesting by itself, they also enable us to analyze a richer model in which firms strategically choose how much information to reveal to their rival. We introduce this model in section 6 of this chapter.

Whenever a firm receives a good signal, $t_i = \underline{t}$, it learns that both firms work on an easy project. Whenever both firms receive a bad signal, they are in one of the following situations. Either the project is difficult, or firms work on an easy

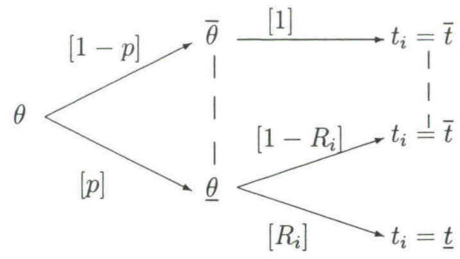

Figure 3.1: Firm i's research stage

project and were simply unlucky. The extent to which firms were unlucky under an easy project depends on firms' research investments, R. The more firms invested in research, the more pessimistic they get about the project's complexity.

In the second stage firms invest in the development of the innovation by spending $D_i \in [0,1]$. Firm i's probability of making a final innovation is then D_i. An easy project, $\theta = \underline{\theta}$, has low marginal costs of development, while a difficult project has higher development costs, $\theta = \overline{\theta}$. In order to keep the model manageable, we assume that firm i's development cost is quadratic in development investment D_i, i.e. $c(D_i;\theta) = \frac{\theta}{2}D_i^2$, for $i = 1,2$. Furthermore, we assume that $\underline{\theta} > 2\Delta$ to obtain interior solutions for firms' development investments.

We assume that firms are risk neutral. For firms' profits we define the following. Given development investments $D \equiv (D_1, D_2)$, firm i's development profits are:

$$\pi_i(D;\theta) \equiv D_i D_j T + D_i(1-D_j)W - \frac{\theta}{2}D_i^2 = D_i(W - \Delta D_j) - \frac{\theta}{2}D_i^2.$$

Then firm i's expected payoff is given by:

$$\Pi_i(R,D) = E_\theta\{\pi_i(D;\theta)|R_i\} - \frac{\rho}{2}R_i^2.$$

We solve the game backwards, and focus on symmetric, pure-strategy Bayes perfect equilibria.

3.3 Benchmark: Efficient Investments

In this section we analyze the efficient outcome for the industry. This means that we calculate the research and development investments that maximize expected total industry's profits. We analyze this solution to understand firms' incentives when all relevant externalities are internalized.[4] We use the efficient outcome as a benchmark to study the effects of competition and private information on equilibrium strategies.

Given public signals, we calculate the efficient information acquisition and development choices by solving the model backwards. In the first subsection we find the efficient development investments, $\overline{D}$. In the second subsection we compute efficient information acquisition investments, $\overline{R}$, given efficient investments in the development stage.[5]

3.3.1 Efficient Development Investments

After the information acquisition stage there are two basic states of the world. Either there is at least one firm that received a good signal, $t \in \{(\underline{t},\underline{t}),(\underline{t},\overline{t}),(\overline{t},\underline{t})\}$, or both firms received a bad signal, $t = (\overline{t},\overline{t})$. In the first case both firms learn that their project is easy, $\theta = \underline{\theta}$, while in the latter case they cannot establish with certainty whether the project is easy or difficult. For both these states of the world we calculate the efficient development investments $\overline{D}$. In the industry's efficient outcome firm i chooses development investment D_i that maximizes expected total development profits, given the signals t, research investment R_i, and expected research investments r:

$$\max_{D_i \in [0,1]} . E_\theta\{\pi_i(D;\theta) + \pi_j(D;\theta)|t; R_i\}, \text{ for } i = 1, 2.$$

Expectations are taken after observing the signals. Firm i's posterior belief of working on an easy project is $\mu_i = \mu(t; R_i, r_j)$. The expected cost of investment parameter is:

$$\mu_i\underline{\theta} + (1 - \mu_i)\overline{\theta} = E(\theta|t; R_i, r_j).$$

Total profit maximization leads to the first-order conditions for development investments:

$$W - 2D_j\Delta = E(\theta|t; R_i, r_j)D_i, \text{ for } i, j = 1, 2, \text{ and } j \neq i.$$

[4]Such a benchmark could be relevant for policy analysis when firms can fully appropriate the social value of their innovation.

[5]We assume that firms' research investments are unobservable in the efficient outcome, in the equilibrium with public signals, and in the equilibrium with private signals. Keeping research investments unobservable throughout the whole analysis enables us to focus on the effects of competition and private information on the firms' signals. It enables us to compare firms' investment in the different benchmarks. In fact, efficient investments for observable and unobservable research investments are identical, since all relevant externalities are internalized.

When there is a firm that receives a good signal in the first stage, the firms know that the project is easy, i.e. $\mu = 1$. Firms' first-order conditions for these beliefs give their optimal development investments, and development profits, for $i = 1, 2$:

$$\overline{D}_i(\underline{t}) = \frac{W}{2\Delta + \underline{\theta}} \text{ and } \pi_i\left(\overline{D}(\underline{t}); \underline{\theta}\right) = \frac{1}{2}\overline{D}_i(\underline{t})W.$$

After both firms received a bad signal, $t = (\overline{t}, \overline{t})$, firms update their beliefs about the project's complexity by applying Bayes' rule: $\mu(\overline{t}, \overline{t}; R_i, r_j) = \frac{p(1-R_i)(1-r_j)}{p(1-R_i)(1-r_j)+1-p}$. Therefore expected costs after two bad signals is:

$$E(\theta|\overline{t}, \overline{t}; R_i) = \underline{\theta} + \phi(R_i, r_j), \text{ with } \phi(R_i, r_j) \equiv \frac{(1-p)(\overline{\theta} - \underline{\theta})}{p(1-R_i)(1-r_j) + 1 - p}.$$

If firms still receive bad signals even though they invested more in information acquisition, firms become more pessimistic about the complexity of the project. Firm i's expected development cost increases in firms' information acquisition investments. The efficient development investments and expected profits are:

$$\begin{aligned} \overline{D}_i(\overline{t}, \overline{t}; R_i) &= \frac{W}{\underline{\theta} + \phi(r) + 2\Delta} \cdot \frac{\underline{\theta} + \phi(r)}{\underline{\theta} + \phi(R_i, r_j)} \text{ and} \\ \overline{\pi}_i(\overline{t}, \overline{t}; R_i) &\equiv E_\theta\left\{\pi_i\left(\overline{D}(\overline{t}, \overline{t}; R_i); \theta\right) \middle| \overline{t}, \overline{t}; R_i\right\} = \frac{1}{2}\overline{D}_i(\overline{t}, \overline{t}; R_i)W. \end{aligned}$$

Since in the efficient outcome expectations will be realized, $\overline{r} = \overline{R}$, firms' efficient investments will be symmetric along the optimizing path. Since $\phi(R) > 0$, expected marginal cost, $\underline{\theta} + \phi(R)$, strictly exceeds marginal cost of investing in an easy project, $\underline{\theta}$. Along the optimizing path it is therefore efficient to invest less after observing $(\overline{t}, \overline{t})$ than after observing a good signal, i.e. $\overline{D}_i(\underline{t}) > \overline{D}_i(\overline{t}, \overline{t}; R_i)$ for $i = 1, 2$. Greater information acquisition efforts that result still in two bad signals make firms more pessimistic about the project's complexity, and expected costs increase. Therefore efficient investments should decrease. After partially differentiating the efficient development investments toward R_i, we establish this:

$$\frac{\partial \overline{D}_i(\overline{t}, \overline{t}; R)}{\partial R_i} = \frac{-p(1-r_j)\phi(R_i, r_j)\overline{D}_i(\overline{t}, \overline{t}; R_i)}{[p(1-R_i)(1-r_j) + 1 - p]\left(\underline{\theta} + \phi(R_i, r_j)\right)} \leq 0,$$

with $i, j = 1, 2, i \neq j$.

We summarize our results in the following lemma.

Lemma 3.1 *The efficient development investments are such that, for $i = 1, 2$:*
(i) along the optimizing path, i.e. $\overline{r}_i = \overline{R}_i$, investments after a good signal exceed those after two bad signals: $\overline{D}_i(\underline{t}) > \overline{D}_i(\bar{t}, \bar{t}; \overline{R}_i)$ for all $\overline{R}_i$;
(ii) investments after two bad signals decrease in information acquisition investments: $\frac{\partial \overline{D}_i(\bar{t},\bar{t};R_i)}{\partial R_i} \leq 0$ for all R_i.

3.3.2 Efficient Research Investments

Given prior beliefs concerning the complexity of the R&D project and given efficient development investments, $\overline{D}$, firms choose research investments, R. Firm i's *ex ante* expected profit, given efficient development investments, is:

$$\begin{aligned}\Pi_i(R_i, \overline{D}) &= (1-p)\pi_i\left(\overline{D}(\bar{t}, \bar{t}|R_i); \bar{\theta}\right) + p(1-R_i)(1-R_j)\pi_i\left(\overline{D}(\bar{t}, \bar{t}|R_i); \underline{\theta}\right) + \\ &\quad + p[1-(1-R_i)(1-R_j)]\pi_i(\overline{D}(\underline{t}); \underline{\theta}) - \frac{\rho}{2}R_i^2.\end{aligned}$$

Efficient information acquisition investments $\overline{R}$ are determined by maximizing $\Pi_i(R_i, \overline{D}) + \Pi_j(R_j, \overline{D})$. When we calculate the first-order conditions, and let expectations on research investments be realized, $r = R$, we obtain:

$$\begin{aligned}\rho R_i &= p(1-R_j)\left(\sum_{\ell=1}^{2}\pi_\ell\left(\overline{D}(\underline{t}); \underline{\theta}\right) - \sum_{\ell=1}^{2}\pi_\ell\left(\overline{D}(\bar{t}, \bar{t}|R); \underline{\theta}\right)\right) \\ &= \frac{p(1-R_j)W^2\phi(R)^2}{(\underline{\theta}+2\Delta)(\underline{\theta}+\phi(R)+2\Delta)^2}, \text{ for } i, j = 1, 2. \qquad (3.1)\end{aligned}$$

That is, marginal costs equal marginal revenues of information acquisition investments. Marginal costs are the direct cost of research investment, ρR_i. The marginal revenue of information gathering investment is the total profit gained from obtaining a good signal and finding out that the project is easy after investing a marginal amount more.

Observe that net marginal revenues in the right hand side of expression (3.1) are positive for all $R_j < 1$. Direct marginal costs are linear and increase monotonically from 0. Therefore efficient information acquisition investments are in the interior of the unit interval, i.e. $0 < \overline{R} < 1$.[6]

[6] Unfortunately, the net revenue function need not always be concave for all R. Especially for big p ($p > \frac{2\Delta+\bar{\theta}}{4\Delta+\bar{\theta}+\underline{\theta}}$) net revenues are convex for small R. For big p and small costs of information acquisition, ρ, there can exist two local optima. We avoid nonconcavities by assuming that the costs of information acquisition investments ρ are big enough to guarantee a unique optimum.

3.4 Race with Public Signals

In this section we calculate the equilibrium of the R&D race where signals t are publicly observable. We derive equilibrium investment decisions of noncooperative firms, and analyze how they relate to the efficient outcome. Research and development investment choices are now made under competition, while firms' information remains symmetric. Again, we solve the game backwards in pure strategy equilibrium.

3.4.1 Public Signal Development Investments

The qualitative properties of equilibrium development investments do not differ from those of efficient investments. Again development investments are high after a good signal and are generically decreasing in research investment. Quantitatively equilibrium investments differ from the efficient ones. Competing firms do not internalize the negative effect of their investment on the expected revenue of their rival. Therefore firms overinvest in development, which is shown in the remainder of this subsection.

After observing the signals, t, and given expected rival's research investment, r_j, firm i updates his beliefs $(\mu(t; R_i, r_j), 1-\mu(t; R_i, r_j))$, and chooses development investments that maximize its expected profit. This gives first-order conditions:

$$(W - \Delta D_j) = E(\theta|t, R_i)D_i, \text{ for } i, j = 1, 2, \text{ and } j \neq i,$$

with $E(\theta|t; R_i, r_j) = \mu(t; R_i, r_j)\underline{\theta} + (1-\mu(t; R_i, r_j))\overline{\theta}$.

When at least one of the firms observes a good signal, firms learn that their project is easy. Firm i's posterior belief is $\mu(\underline{t}, .) = 1$, and its first-order condition gives its reaction function for development investments. Firms' reaction functions slope downward. When firm j invests more in development, it becomes less likely that firm i will be the winner of the race, which depresses its expected prize, and its incentive to invest. Both firms' reaction functions together determine the symmetric equilibrium research investments and profits:

$$\widehat{D}_i(\underline{t}) = \frac{W}{\underline{\theta} + \Delta} \text{ and } \pi_i\left(\widehat{D}(\underline{t}); \underline{\theta}\right) = \frac{1}{2}\underline{\theta}\widehat{D}_i(\underline{t})^2, \text{ for } i = 1, 2.$$

Whenever both firms receive a bad signal, they remain uncertain about the true state of the project. Depending on the information acquisition investments, each firm updates its beliefs about the project's complexity, and forms beliefs $\mu(\overline{t}, \overline{t}; R_i, r_j) = \frac{p(1-R_i)(1-r_j)}{p(1-R_i)(1-r_j)+1-p}$. From both firms' reaction functions we derive equilibrium investments and expected profits:

$$\begin{aligned}\widehat{D}_i(\bar{t},\bar{t};R_i) &= \frac{W}{\underline{\theta}+\phi(r)+\Delta}\cdot\frac{\underline{\theta}+\phi(r)}{\underline{\theta}+\phi(R_i,r_j)} \text{ and}\\ \widehat{\pi}_i(\bar{t},\bar{t};R_i) &\equiv E_\theta\left\{\pi_i\left((\widehat{D}(\bar{t},\bar{t};R_i);\theta)\right|\bar{t},\bar{t};R_i\right\} = \frac{1}{2}(\underline{\theta}+\phi(R_i,r_j))\widehat{D}_i(R_i)^2.\end{aligned}$$

Along the equilibrium path expectations about rival's research investments are realized, i.e. $\widehat{r}_i = \widehat{R}_i$ for $i = 1,2$, and we obtain that $\widehat{D}_i(\bar{t},\bar{t};\widehat{R}_i) < \widehat{D}_i(\underline{t})$ for all $\widehat{R}_i$.

Suppose that firms' research investments only result in bad signals. The greater a firm's information acquisition investments, R_i, the higher its expected costs of development investments, and the more cautious the development investments. Pessimistic firms invest less than optimistic ones. Therefore equilibrium development investments decrease in research investments, given bad signals:

$$\frac{\partial\widehat{D}_i(\bar{t},\bar{t};R_i)}{\partial R_i} = \frac{-p(1-r_j)\phi(R_i,r_j)\widehat{D}_i(\bar{t},\bar{t};R_i)}{(p(1-R_i)(1-r_j)+1-p)\left(\underline{\theta}+\phi(R_i,r_j)\right)} \leq 0. \tag{3.2}$$

These findings are qualitatively identical to those summarized in lemma 3.1 for efficient development investments.

Given a signal combination t, firms overinvest compared to the efficient investments: $\widehat{D}_i(t;R_i) > \overline{D}_i(t;R_i)$. This is due to the fact that competing firms do not internalize the negative effect of their own development investments on their rival's expected revenues. Firm i's investment D_i marginally decreases firm j's revenue with $D_j\Delta$. Therefore firms invest more aggressively than would be efficient for them. This is a common observation in the literature on R&D races. Competition leads to overinvestments, which is stated in the following proposition.

Lemma 3.2 *For the game with public signals firms overinvest in equilibrium:* $\widehat{D}_i(t;R_i) > \overline{D}_i(t;R_i)$ *for all* t, R, *and* r, *with* $i = 1,2$. *All qualitative properties of lemma 3.1 hold true for* $\widehat{D}_i(.)$ *too.*

3.4.2 Public Signal Research Investments

Working backwards, we calculate the equilibrium information acquisition investments given the equilibrium development investments. Firm i chooses R_i that maximizes expected profit $\Pi_i(R,\widehat{D})$, given equilibrium development investments, $\widehat{D}$. Profit maximization leads to the following research equilibrium condition:

$$\begin{aligned}\rho R_i &= p(1-R_j)\left\{\pi_i\left(\widehat{D}(\underline{t});\underline{\theta}\right) - \pi_i\left(\widehat{D}(\bar{t},\bar{t}|R_i);\underline{\theta}\right)\right\} + \\ &\quad +[p(1-R_i)(1-R_j)+1-p]\frac{\partial\widehat{\pi}_i(\bar{t},\bar{t};R_i)}{\partial R_i}.\end{aligned} \tag{3.3}$$

Notice that marginal revenues contain two informational effects now. The first effect captures the marginal increase in revenue after more research results in jumping from a bad to a good signal. However, when bad signals persist despite increased research, then the increase in research leads to growing pessimism and lower expected revenues. The second effect captures this loss in expected revenues due to firms' growing pessimism after persistence of bad news. Firms internalize the second effect in the efficient outcome.

In equilibrium firms' expectations about research investments are realized, i.e. $\widehat{r}_i = \widehat{R}_i$. Therefore we can rewrite the equilibrium condition for $\widehat{R}_i$ to:

$$\begin{aligned}\rho R_i &= p(1-R_j)\frac{1}{2}\underline{\theta}\left\{\widehat{D}_i(\underline{t})^2 - \widehat{D}_i(\overline{t},\overline{t};R_i)^2\right\} + \\ &\quad +[p(1-R_i)(1-R_j)+1-p](\underline{\theta}+\phi(R))\widehat{D}_i(\overline{t},\overline{t};R_i)\frac{\partial \widehat{D}_i(\overline{t},\overline{t};R_i)}{\partial R_i} \\ &= \max\left\{0, \widehat{MR}(R)\right\},\end{aligned}$$

with

$$\widehat{MR}(R) \equiv \frac{p(1-R_j)W^2\phi(R)\left(\frac{1}{2}\underline{\theta}\phi(R) - (\underline{\theta}+\Delta)\Delta\right)}{(\underline{\theta}+\Delta)^2(\underline{\theta}+\phi(R)+\Delta)^2}. \tag{3.4}$$

When we focus on symmetric equilibria ($\widehat{R}_1 = \widehat{R}_2$), we can show that firms underinvest in research. Since signals are public, and firms can learn from each others' signals, they have an incentive to free-ride on their rival's information acquisition investments.

Proposition 3.1 *Symmetric equilibrium research investments in the race with public signals do not exceed the efficient investments:* $\overline{R}_i \geq \widehat{R}_i$ *for* $i = 1, 2$. *For interior equilibrium and efficient research investments the inequality is strict.*

It is efficient to invest more than $\widehat{R}_i$, because the efficient investments internalize the positive externality of informational spillovers among firms. If firm i's research leads to a good signal, this improves both its own and its rival's expected profit. On top of that each firm takes into account that the decrease in its equilibrium development investments from higher research investments after bad news improves its rival's development profits. Internalizing these two effects results in higher research investments.

It would be an interesting exercise to characterize firms' expected equilibrium development investments given their equilibrium research investments, and characterize expected equilibrium profits. This would shed more light on the interaction between research and development. Such an exercise awaits future research.

In these two subsections we saw that firms would improve their profits if they could find a way to both lower development investments $\widehat{D}$, and increase research investments $\widehat{R}$. In the next subsection we will show that revenue sharing provides firms with a way to achieve this.

3.4.3 Effects of Revenue Sharing

So far we assumed that in the race the winner takes all. This is, however, only an extreme way of distributing revenues from the innovation among firms. In general the loser of the race gets a share, σ, of the revenues. In US sports tournaments revenue sharing is used to decrease firms' overinvestments in talent. Cook and Frank (1995) observe the following:

> "*Revenue sharing — the practice whereby team owners pool and share gate and television revenues with each other — is another common device for limiting expenditures. Because fans strongly prefer to watch winning teams, there is a strong link between a team's winning percentage and the amount of television and gate revenues the team generates. Without revenue sharing, owners thus face powerful incentives to bid for star players, coaches, scouts, and other inputs that make winning more likely. Revenue sharing weakens these incentives and thus helps to restrain player salaries and other key costs.*" [Frank and Cook (1995), pp 169]

In the race for a patent revenue sharing should have the same desirable effect on development overinvestments. But in the race for a patent revenue sharing has an effect on the firms' incentives to invest in development but also on incentives to invest in information acquisition. In what direction these effects point, is studied here. We argue that revenue sharing introduces a free-rider incentive in the development stage which depresses development investments. Revenue sharing introduces the following effect for research. When research investments result in a good signal, then this increases the expected revenue of a firm's rival too. Since part of the revenues are shared, this gives each firm a bigger incentive to invest in research. An effect in the opposite direction results from the fact that in absolute terms firms' development investments are lower than in the "winner-takes-all" race, which would reduce the incentive to invest in research. However, initially both investments change in the right direction. This is the main point made in the remainder of this subsection.

Observe that for $\sigma = 0$, we are in the "winner-take-all" race, and for $\sigma = \frac{1}{2}$ firms share the prize equally. Such a share in the revenue affects firms' incentives to invest. In this subsection we characterize the revenue share that brings firms' equilibrium investments closer to the efficient investments. In the following paragraphs we solve the game backwards for any revenue share $\sigma \in [0,1]$.

■ Given revenue share σ and cost parameter θ development profits are:

$$\begin{aligned}\pi_i(D;\theta|\sigma) &= D_iD_jT + D_i(1-D_j)(1-\sigma)W + (1-D_i)D_j\sigma W - \frac{1}{2}\theta D_i^2 \\ &= \pi_i(D;\theta) + \sigma\,(D_j - D_i)\,W.\end{aligned}$$

This changes first-order conditions into:

$$(1-\sigma)W - D_j\Delta = E(\theta|t,R_i)D_i,$$

with $E(\theta|t,R_i)$ the expected costs, depending on first-stage signals and research investment. Note that marginal expected revenues are reduced with σW from introducing revenue sharing, while marginal costs remain the same. Therefore, equilibrium development investments decrease in the revenue share σ. The marginal effect of firm i's development investment on firm j's expected profits is now $\sigma W - D_j\Delta$. Hence the negative externality $-D_j\Delta$ of the "winner-takes-all" race is reduced by σW. Sharing revenues makes firms less aggressive competitors, because their profits are more interdependent. Development investments and profits are:

$$\begin{aligned}\widehat{D}_i(\sigma) &= (1-\sigma)\widehat{D}_i, \text{ and} \\ \pi_i(\widehat{D}(\sigma);\theta^E|\sigma) &= (1-\sigma)^2\widehat{\pi}_i(t;R_i) + (1-\sigma)\sigma\widehat{D}_jW.\end{aligned}$$

for $i = 1,2$. Notice that equilibrium development investments range from 0, in the "loser-takes-all" race ($\sigma = 1$), to $\widehat{D}_i$, in the "winner-takes-all" race ($\sigma = 0$). In the "equal-sharing" race, $\sigma = \frac{1}{2}$, firms underinvest in development. From the first-order conditions $\frac{1}{2}W - \widehat{D}_j(\frac{1}{2})\Delta = \theta^E\widehat{D}_i(\frac{1}{2})$ and $\frac{1}{2}W - \overline{D}_j\Delta = \frac{1}{2}\theta^E\overline{D}_i$, and the symmetry of equilibrium it follows immediately that $\widehat{D}_i(\frac{1}{2}) < \overline{D}_i$.

These results are summarized in the following proposition.

Proposition 3.2 *For the race with public signals and revenue share σ the following holds: (i) Equilibrium development investments decrease in the revenue share:* $\frac{\partial \widehat{D}_i(\sigma)}{\partial \sigma} < 0$ *for all* σ.
(ii) Firms underinvest in the "equal-sharing" development equilibrium: $\widehat{D}_i(t, R_i|\frac{1}{2}) \leq \overline{D}_i(t, R_i)$ *for all* t, R_i, r.

■ Now we calculate equilibrium research investments given equilibrium development investments. To derive first-order conditions, it is useful to recall how equilibrium development profits with revenue sharing relate to those without revenue sharing. This gives the following first-order conditions for firm i's research.

$$\begin{aligned}\rho R_i &= (1-\sigma)^2 p(1-R_j)\left\{\pi_i\left(\widehat{D}(\underline{t});\underline{\theta}\right) - \pi_i\left(\widehat{D}(\overline{t},\overline{t};R_i);\underline{\theta}\right)\right\} + \\ &\quad +(1-\sigma)^2[p(1-R_i)(1-R_j)+1-p]\frac{\partial \widehat{\pi}_i(\overline{t},\overline{t};R_i)}{\partial R_i} + \\ &\quad +\sigma(1-\sigma)p(1-R_j)W\left\{\widehat{D}_j(\underline{t}) - \widehat{D}_j(\overline{t},\overline{t};r_j)\right\}\end{aligned}$$

Both firms' first-order conditions determine the research equilibrium investments. The first two terms of firm i's marginal revenues trade off similar informational effects as in the previous subsection. They are its "winner-takes-all" marginal revenues, as in expression (3.3), where we correct for the fact that the firm can only keep $(1-\sigma)$ of its generated revenue, and that firms' incentives to invest in development are reduced with factor $(1-\sigma)$. The last term is exactly the change in revenue that firm i expects to receive from its rival after making him more optimistic by providing the industry with a good signal. Remember that share σ of firm j's development revenues spill over to firm i, while equilibrium development investments are reduced with factor $(1-\sigma)$.

In equilibrium expectations are realized. The equilibrium research investments $\widehat{R}(\sigma)$ are then the solution to:

$$\rho R_i = \max\left\{0, (1-\sigma)\left((1-\sigma)\widehat{MR}(R) + \sigma\widehat{MQ}(R)\right)\right\}, \tag{3.5}$$

with $\widehat{MR}(R)$ as defined in (3.4), and

$$\widehat{MQ}(R) \equiv p(1-R_j)W\left\{\widehat{D}_j(\underline{t}) - \widehat{D}_j(\overline{t},\overline{t};r_j)\right\} = \frac{p(1-R_j)W^2\phi(R)}{(\underline{\theta}+\Delta)(\underline{\theta}+\phi(R)+\Delta)}. \tag{3.6}$$

Due to the model's symmetry, firms' research investments are symmetric. In the remainder of this subsection we characterize the equilibrium research investments, $\widehat{R}(\sigma)$, by deriving how investment depends on the industry's prize share σ.

We show that research investments do not decrease after introducing a sufficiently small revenue share $\sigma > 0$. Increasing the revenue share has two conflicting effects. At the one hand it internalizes a fraction of the positive informational externalities from research, which increases firms' incentives to invest in research. However, when the revenue share is increased this shrinks the development investments, and consequently firms' revenues of research. The equilibrium research investment trades off internalizing informational externalities of research against free-rider effects in development. This is summarized in the following proposition.

Proposition 3.3 *For the race with public signals in which firms make positive research investments in the "winner-takes-all" race, $\widehat{R}_i(0) > 0$, there is a revenue share $\widehat{\sigma} \in (0, \frac{1}{2})$ such that equilibrium research investments are increasing for all $\sigma < \widehat{\sigma}$ and decreasing for all $\sigma > \widehat{\sigma}$.*

A direct consequence of this proposition is that total profits are increased by introducing a (small) positive revenue share in the "winner-takes-all" race. Since both overinvestments in development and underinvestments in research are reduced, total profits are increased.

3.5 Race with Private Signals

In the previous section we assumed that the firms' signals are public. However such an assumption need not be realistic. In this section we make the assumption that information is private to the firms and cannot be revealed to rivals. We derive the equilibrium investment levels and compare them with those of firms with public signals.

3.5.1 Private Signal Development Investments

When signals are private information to firms, firms can condition their development investments on their own signal only. A good signal received by one firm does not imply that both firms become optimistic about development costs. It is possible that the other firm is unlucky and receives a bad signal. Therefore the expected rival to a firm with a good private signal is less aggressive than the rival to a firm with a good public signal. This makes equilibrium development investments of a good private signal firm exceed those of a good public signal firm. When both firms receive a bad private signal, a firm faces the following trade-off. On the one hand a firm with only one bad signal is more optimistic about development costs, because it does not pool its information with its rival. However, on the other hand, the firm expects a more aggressive rival compared to the race with public signals. The first effect encourages, while the second effect discourages development investments. We show that the informational effect dominates the strategic effect along the equilibrium path. This is done in the remainder of this subsection.

Given private signals, and firm i expects its rival's information acquisition investments are r_j, its reaction functions are the following:

$$\begin{aligned}
\underline{\theta} D_i^*(\underline{t}) &= (1-\sigma)W - \left(r_j D_j^*(\underline{t}) + (1-r_j) D_j^*(\bar{t})\right)\Delta, \\
\left(\underline{\theta} + \varphi(R_i)\right) D_i^*(\bar{t}; R_i) &= (1-\sigma)W - \left(P(R_i) D_j^*(\underline{t}) + [1-P(R_i)] D_j^*(\bar{t})\right)\Delta, \\
\text{with } \varphi(R_i) &= \frac{(1-p)(\overline{\theta}-\underline{\theta})}{p(1-R_i)+1-p} \text{ and } P(R_i) = \frac{p(1-R_i)r_j}{p(1-R_i)+1-p}.
\end{aligned}$$

The equilibrium development investments of a firm with a bad signal, $D_i^*(\bar{t}; R_i)$, depends on its investments in information acquisition, R_i. If the firm keeps receiving a bad signal despite the fact that it invested more in information acquisition, it becomes more pessimistic about the complexity of the project. The firm's growing pessimism has two effects. First, the firm expects higher development costs. This decreases its development investments. Second, it attaches a stronger belief to the contingency that its rival also receives a bad signal, i.e. $P(R_i)$ decreases. A rival with a bad signal is a weaker competitor, which encourages the firm's development investments. These two effects are captured in the following expression.

$$\frac{\partial D_i^*(\bar{t}; R_i)}{\partial R_i} = \frac{-p\varphi(R_i) D_i^*(\bar{t}; R_i)}{\left(p(1-r_j)+1-p\right)\left(\underline{\theta}+\varphi(R_i)\right)} + \frac{p(1-p)r_j\left(D_j^*(\underline{t}) - D_j^*(\bar{t}; r_j)\right)\Delta}{\left(p(1-r_j)+1-p\right)^2\left(\underline{\theta}+\varphi(R_i)\right)}.$$

Along the equilibrium path, where expectations are realized and symmetric, i.e. $r_i^* = R_i^* = R$ for $i = 1, 2$, the direct effect outweighs the indirect effect. Development investments of a firm with bad news decreases in its research investments. Expected equilibrium development profits given $t_i = \underline{t}$ and $t_i = \bar{t}$ are respectively:

$$\begin{aligned}
\pi_i^*(\underline{t}) &= \frac{1}{2}\underline{\theta} D_i^*(\underline{t})^2 + \sigma\left(r_j D_j^*(\underline{t}) + (1-r_j) D_j^*(\bar{t})\right) W \text{ and} \\
\pi_i^*(\bar{t}; R_i) &= \frac{1}{2}\left(\underline{\theta}+\varphi(R_i)\right) D_i^*(\bar{t})^2 + \sigma\left(P(R_i) D_j^*(\underline{t}) + (1-P(R_i)) D_j^*(\bar{t})\right) W.
\end{aligned}$$

Along the equilibrium path, where firms invest equal amounts in information acquisition and expectations concerning investments are fulfilled, $r_i = R_i = R$, development investments are the following:

$$
\begin{aligned}
D_i^*(\underline{t};R) &= \frac{(1-\sigma)\left(\underline{\theta}+\varphi(R)+(R-P(R))\Delta\right)W}{(\underline{\theta}+R\Delta)\left(\underline{\theta}+\varphi(R)+(1-P(R))\Delta\right)-(1-R)P(R)\Delta^2},\\
D_i^*(\overline{t};R) &= \frac{(1-\sigma)\left(\underline{\theta}+(R-P(R))\Delta\right)W}{(\underline{\theta}+R\Delta)\left(\underline{\theta}+\varphi(R)+(1-P(R))\Delta\right)-(1-R)P(R)\Delta^2}.
\end{aligned}
$$

It is immediate that $D_i^*(\underline{t};R) > D_i^*(\overline{t};R)$. A firm with a bad signal is more reluctant to invest in the development of the intermediate innovation than a firm with a good signal.

Since a rival with a bad signal invests less than one with a good signal, a $\underline{t}$-firm expects its rival to invest less aggressively than with public signals. This means that a firm with a good private signal invests more in development than a firm with a good public signal, provided that information acquisition investments are symmetric ($R_1 = R_2$) and expectations are realized: $D_i^*(\underline{t};R) \geq \widehat{D}_i(\underline{t})$ for all R.

Now consider the situation in which nature chose two bad signals, $(\overline{t},\overline{t})$. For each firm there are two effects when we turn from a public to a private bad signal. First, the firm becomes more optimistic about its costs. Since it conditions its beliefs only on its own bad signal, expected cost is lower. This drives the firm's investments up. Second, it expects higher investments from its rival. This decreases the firm's investment incentives. The direct cost effect outweighs the indirect effect of rival's expected investments, when information acquisition investments are symmetric and expectations are realized. Therefore a firm with a private bad signal invests more in development than a firm with bad public signal: $D_i^*(\overline{t};R) > \widehat{D}_i(\overline{t},\overline{t};R)$ for all R.

In the situation in which there is one firm who receives a good signal while the other receives a bad signal, equilibrium investments for firms with private signals are lower than investments with publicly observable signals. That is, $D_i^*(\underline{t})+D_i^*(\overline{t})-2\widehat{D}_i(\underline{t},\overline{t}) < 0$. Again, this holds provided that $R_1 = R_2$, and that expectations are fulfilled.

We summarize the findings of this subsection in the following proposition.

Proposition 3.4 *In the race with private signals where expected research investments are symmetric and realized, with $r_i^* = R_i^* = R < 1$, equilibrium development investments are such that, for $i = 1, 2$:*
(i) $D_i^*(\underline{t};R) > D_i^*(\overline{t};R)$, and $\frac{\partial D^*(\overline{t};R)}{\partial R_i} < 0$,
(ii) $D_i^*(\underline{t};R) > \widehat{D}_i(\underline{t})$ and $D_i^*(\overline{t};R) > \widehat{D}_i(\overline{t},\overline{t};R)$.

3.5.2 Private Signal Research Investments

In the first stage of the race firms invest in information acquisition. The information that each firm acquires remains private information for that firm. The free-rider incentive in research that exists in the race with public signals is no longer present. Firms will therefore invest more in research when the winner takes all. When firms share revenues, it is not clear in which direction equilibrium research investments change. We have seen that for public signals there are two free-rider effects. First there is the direct effect, that a firm's own revenues are negatively affected because also the firm's rival learns from its research. But, second, the rival's learning has a positive indirect effect through revenue sharing. We substantiate these observations in the remainder of this subsection.

First-order conditions for equilibrium research investments R^* are the following:

$$\begin{aligned}
\rho R_i &= p\frac{1}{2}\underline{\theta}\left[D_i^*(\underline{t})^2 - D_i^*(\overline{t};R_i)^2\right] + \\
&\quad + \left[p(1-R_i)+1-p\right]\left(\underline{\theta}+\varphi(R_i)\right)D_i^*(\overline{t};R_i)\frac{\partial D_i^*(\overline{t};R_i)}{\partial R_i} \\
&= p\left[\frac{1}{2}\underline{\theta}D_i^*(\underline{t})^2 - \left(\frac{1}{2}\underline{\theta}+\varphi(R_i)\right)D_i^*(\overline{t};R_i)^2\right] + \\
&\quad + \frac{p(1-p)R_jD_i^*(\overline{t})\left(D_j^*(\underline{t}) - D_j^*(\overline{t};R_j)\right)\Delta}{(p(1-R_j)+1-p)}.
\end{aligned}$$

If we focus on symmetric equilibria, we get the following:

$$\rho R = \frac{\frac{1}{2}p\underline{\theta}\varphi(R)^2(1-\sigma)^2W^2}{\left(\left(\underline{\theta}+R\Delta\right)\left(\underline{\theta}+\varphi(R)+(1-P(R))\Delta\right)-(1-R)P(R)\Delta^2\right)^2}. \tag{3.7}$$

A marginal increase in firm i's research investments that gives firm i a good signal does not directly affect firm j's investments, because the firm's signal is private information. Therefore the revenue that firm i receives from its rival, through revenue share σ, is no longer affected by its research investments. The incentive to invest in research for firm i now only depends on the appropriability of its research investments, which is the share of its own revenue that the firm keeps, i.e. $1-\sigma$. The more revenue spills over to the rival, the less valuable its own research becomes for the firm. Therefore we observe that each firm's equilibrium research investment decreases in the revenue share σ. This is confirmed in the following lemma.

Lemma 3.3 *In the race with private signals, for all revenue shares $\sigma \in [0,1]$ firms' research investments decrease in the revenue share: $\frac{\partial R_i^*(\sigma)}{\partial \sigma} < 0$ for $i = 1, 2$.*

In the "winner-takes-all" race equilibrium research investments in acquiring private signals exceed those of the equilibrium with public signals. Since firms can no longer free ride on their rival's investments and signals, they have an incentive to invest more in information acquisition. This is stated in the following proposition.

Proposition 3.5 *In the "winner-takes-all " race ($\sigma = 0$) firms invest in equilibrium more in acquiring private than public signals: $R_i^*(0) \geq \widehat{R}_i(0)$. This holds with strict inequality whenever firms choose interior equilibrium research investments.*

More insight in the interaction between research and development could be gained from the characterization of firms' expected equilibrium development investments given equilibrium research investments, and their equilibrium profits. An overall comparison between equilibrium development investments and equilibrium profits for public and private signals would close the analysis. This exercise awaits future research.

3.6 Strategic Revelation

In this section we extend the game by adding an information revelation stage. After firms invested in research and received their private signal, firms choose what message to send to their rival. After firms received each other's message, they invest in development. Firms have an incentive to manipulate their information in order to alter their rival's beliefs, and consequently change competition in the development stage in their favor. Firms in a "winner-takes-all" race have an incentive to make their rival as pessimistic as possible to discourage rival's development investments. For high revenue shares firms have an incentive to make their rival as optimistic as possible. An optimistic rival invests relatively much, and the revealing firm can take a free ride on the revenue generated by those investments. The extent to which firms can actually manipulate rival's beliefs and investments and the direction in which this happens is the main topic of this section. Typically we are also interested in learning in what direction firms want to shift rival's investments for intermediate revenue shares.

We make two distinct informational assumptions. First we analyze what information is revealed when firms' information is non-verifiable. We do this in the next subsection. How firms' incentives and possibilities to reveal information are affected when information is costlessly verifiable is studied in the second subsection.

3.6.1 Non-verifiable Information

In this subsection we assume that firms cannot verify the truthfulness of their rival's messages. This makes it costless for firms to lie about their signal. Since lying is for free and there is always a firm with incentives to lie, firms never fully reveal their signals. We establish this in this subsection. Our contribution is here to show that even for intermediate revenue shares firms' incentives are not aligned. Naturally, a firm's rival is aware of the strategic nature of the firm's messages, and will be less willing to rely on the firm's information. In fact we can show that there always is an equilibrium in which no information is revealed. That is, investments for the race in private signals are equilibrium investments in this situation.

Since information is non-verifiable, firms can make any statement about their information they like. Formally, after each firm received its private signal, firms simultaneously choose their revelation rules $(\tau_i(\underline{t}, R_i), \tau_i(\overline{t}, R_i))$, with $\tau_i(t_i, R_i) \in \{\underline{t}, \overline{t}\}$, and reveal information $\widetilde{\tau}_i \in \{\tau_i(t_i, R_i) | t_i = \underline{t}, \overline{t} \text{ and } 0 \leq R_i \leq 1\}$ accordingly. Information is not verifiable for firms. For example, revelation rule $(\tau_i(\underline{t}, R_i), \tau_i(\overline{t}, R_i)) \equiv (\underline{t}, \overline{t})$ gives full revelation, while rules $(\tau_i(\underline{t}, R_i), \tau_i(\overline{t}, R_i)) \equiv (\overline{t}, \overline{t})$ and $(\underline{t}, \underline{t})$ do not reveal any information to the rival firm. After messages are sent, firms simultaneously invest in development.

A natural first step of analysis is to see whether firms voluntarily reveal all their information in equilibrium. This would give us investments of the race with public signals. First consider the "winner-takes-all" race. In this race each firm has an incentive to make its rival invest as little as possible. If it is expected that a firm fully reveals its information, then this firm has an incentive to always send bad news. That is, it always states $t = \overline{t}$. The rival believes this is truthfully revealed information, and becomes pessimistic. The pessimistic rival invests little in development of the prototype, which increases the expected profit of the sender of bad news. Second, consider the "equal-sharing" race where firms believe that their rival fully reveals information. In an "equal-sharing" race each firm has an incentive to make its rival's investments as big as possible in order to take a free ride on those investments. Then a firm has an incentive to always send good news. The firm's rival believes that $\underline{t}$ was observed, and becomes optimistic about the costs of investment. The rival's investments increase, and the sender of good news takes a free ride on these high investments. Similar incentives to under- or overstate information exist for other revenue shares. And full disclosure does never happen in equilibrium, as is stated in the following proposition.

Proposition 3.6 *For all revenue shares $\sigma \in [0,1]$, there does not exist an equilibrium of the game with strategic revelation of non-verifiable information in which signals are completely revealed.*

This result indicates that the assumption of publicly observable signals, as in Choi (1991) and Malueg and Tsutsui (1997), is indeed a strong one. When the assumption is relaxed and signals can be costlessly misrepresented, complete revelation no longer happens in equilibrium.

The polar case of complete revelation is no revelation of any information. No revelation of information can always be sustained as an equilibrium. Given that the statements of firms contain no information whatsoever, firms ignore them. Since statements are ignored, neither truthful nor false statements affect rival's investments. Therefore firms are indifferent between all statements, and it is optimal to choose the non-revealing rule that is consistent with equilibrium beliefs. This is stated in the following lemma.

Lemma 3.4 *There is an equilibrium of the game with strategic revelation of non-verifiable information in which no information is revealed for any revenue share $\sigma \in [0,1]$.*

This result is similar to that of Ziv (1993), and is standard for models with non-verifiable signals. The paper by Ziv focuses on the incentives of Cournot duopolists to understate costs of producing homogeneous products. In our analysis we consider a situation in which revenue sharing affects firms' incentives. And we show that irrespective of how firms share the revenue from innovation, they never reveal their information. Depending on how much of the revenue is shared between firms, firms have an incentive to give less (low σ), more (high σ), or both less and more (intermediate σ) favorable information to the rivals.

It would be interesting to see whether there are revenue shares for which revelation of some information will be chosen in equilibrium. This question awaits future research.

3.6.2 Verifiable Information

In the previous subsection we assumed that firms can costlessly misrepresent their private signal. Therefore credible revelation of information is not possible in equilibrium. A natural question to ask is how the results are affected when information is costlessly verifiable. The only choice that a firm with verifiable information has, is to either disclose its information or conceal it. For low (resp. high) revenue shares firms have an incentive to disclose only bad (resp. good) news. A firm's rival anticipates this and knows that a concealing firm's cost signal is low (resp. high). This evaporates a firm's possibilities to effectively conceal information. However for intermediate revenue shares complete disclosure is not an equilibrium strategy. For intermediate shares both the high- and low-cost type of firms have an incentive to conceal, and can therefore credibly do so. This is shown in the remainder of this subsection.

The seminal paper by Okuno-Fujiwara *et al.* (1990) gives sufficient conditions on firms' strategic interaction and information under which an equilibrium with full disclosure of private information with sceptical inferences exists. For our R&D race neither sufficient condition 4c nor 4d from Okuno-Fujiwara *et al.* (1990) are met. Assumption 4c (resp. 4d) states that as a firm's signal increases, his reaction curve shifts out (resp. in) while his rival's reaction function shifts in (resp. out) or stays the same.

In our model firms' signals, and expected profits, are correlated. Therefore firm i's marginal expected development profit is non-increasing both in its own and its rival's signal. The negative relationship between a firm's disclosure and its own marginal profit is a strategic effect. After disclosing verifiable good news, a firm discloses to be an aggressive development investor. The negative relationship between a firm's signal and its rival's marginal profit is caused by the informational effect of disclosure. Disclosure of good news by one firm makes the other firm more optimistic which shifts out its development reaction function.

The violation of the sufficient conditions for complete revelation raises the question whether the "unraveling" result still goes through. Okuno-Fujiwara *et al.* discuss a common value example in which neither condition 4c nor 4d is satisfied, but full disclosure is still established. The result is obtained here because the strategic effect dominates the informational effect. In our model the informational effect dominates the strategic effect, and we obtain a similar result for extreme revenue shares.

Proposition 3.7 *When firms' signals are costlessly verifiable after revelation, then there are revenue shares $\overline{\sigma}$ and $\underline{\sigma}$, with $0 < \overline{\sigma} < \underline{\sigma} < 1$, such that:*
(i) for $\sigma \leq \overline{\sigma}$ firms fully disclose in equilibrium with skeptical inferences,
(ii) for $\overline{\sigma} < \sigma < \underline{\sigma}$ no inferences support full disclosure in equilibrium,
(iii) for $\sigma > \underline{\sigma}$ firms fully disclose in equilibrium with skeptical inferences.

Note that skeptical inferences of (i) and (iii) are not identical. For revenue shares

$\sigma \leq \overline{\sigma}$ firms have an incentive to conceal good news, while they have an incentive to disclose bad news. Therefore firms infer that a concealing firm received signal $\underline{t}$ under (i). These beliefs make strategic concealment of information unprofitable. For revenue shares that exceed $\underline{\sigma}$ firms have an incentive to conceal only bad news. Hence for (iii) firms rationally infer that a concealing rival has signal $\overline{t}$, which establishes full revelation.

For extreme revenue shares the verifiability of firms' information enables a firm to unravel its rival's private information, as in Grossman (1981) and Milgrom (1981). Such a result is the opposite of our results on revelation in the previous subsection. For non-verifiable signals firms cannot credibly reveal any information, while for verifiable signals firms cannot credibly conceal information from their rival.

Under (ii) both firms have an incentive to misrepresent their information, and full disclosure is not chosen in equilibrium. For intermediate revenue shares different effects dominate for different firm types. A firm who received a bad signal has an incentive to conceal since it makes his rival more optimistic about the costs of investment. The rival will invest more in development, and the high-signal firm can take a free ride on its rival's higher expected revenue. A firm with a good signal has an incentive to conceal information, and discourage its rival in the development stage. For the good-signal firm the informational effect outweighs the free-rider effect. A similar result is found in a different setting by Hendricks and Kovenock (1989).

3.7 Observable Research Investments

In this section we discuss how results depend on the non-observability of research investments. We illustrate the effect of publicly observable research investments by looking at the case in which signals are public.

Changes in one firm's publicly observable research investments affect both firms' beliefs. When firms keep receiving bad news after a firm increases its research investments, this has two conflicting effects. First the usual effect is that the investing firm decreases its development investment, because it becomes more pessimistic. However, also the firm's rival becomes more pessimistic, and contracts its development investments. This spillover effect gives the firm a bigger incentive to invest in development. Therefore increases in observable research investments make development investments after bad signals decrease less steeply than unobservable research investments. This has two consequences for equilibrium research investments. First the spillover effect makes a firm's own expected revenues of observable research investments bigger than those of unobservable investments. Therefore equilibrium observable research investments exceed equilibrium unobservable investments in the "winner-takes-all" race. The second observation is that the spillover effect decreases rivals' expected revenue. Therefore the marginal benefit of revenue sharing is reduced, which makes observable equilibrium research investments smaller than unobservable investments in the "equal-sharing" race. A more detailed discussion of these effects is given in the remainder of this section.

With observable research investments equilibrium development investments D^o depend on the research investments of both firms, R:

$$D_i^o(\underline{t}) = \frac{(1-\sigma)W}{\underline{\theta}+\Delta}, \text{ and } D_i^o(\bar{t},\bar{t};R) = \frac{(1-\sigma)W}{\underline{\theta}+\phi(R)+\Delta},$$

and

$$\frac{\partial D_i^o(\bar{t},\bar{t};R)}{\partial R_i} = \frac{-p(1-R_j)\phi(R)D_i^o(\bar{t},\bar{t};R)}{[p(1-R_i)(1-R_j)+1-p]\left(\underline{\theta}+\phi(R)+\Delta\right)} \leq 0,$$

for $i = 1,2$.When we compare this expression with that in equation (3.2) where expectations concerning research are realized, $r_j = R_j$ for $j = 1,2$, we note the following:

$$\frac{\partial \widehat{D}_i(\bar{t},\bar{t};R)}{\partial R_i} < \frac{\partial D_i^o(\bar{t},\bar{t};R)}{\partial R_i} \leq 0.$$

When research investments are observable, firm i's equilibrium development investments are less sensitive to unilateral investment changes. This is caused by the following spillover effect. When firm i's research investment is observable, and firm i increases research investments while the signals remain $(\bar{t},\bar{t})$, not only firm i, but also firm j becomes more pessimistic. Firm j therefore decreases its development investments. Since development investments are strategic substitutes, this countervails firm i's direct decrease in development investments. This spillover effect reduces the direct effect of firm i's own growing pessimism.

The equilibrium profits, given cost of investment θ and equilibrium development investments D^o, is:

$$\pi_i(D^o(\sigma);\theta) = (1-\sigma)\left((1-\sigma)\frac{1}{2}\theta(D_i^o)^2 + \sigma W D_j^o\right).$$

The equilibrium condition for research investments, R^o, becomes:

$$\rho R_i = (1-\sigma)\left((1-\sigma)MR^o(R) + \sigma MQ^o(R)\right),$$

with

$$
\begin{aligned}
MR^o(R) &= p(1-R_j)\frac{1}{2}\underline{\theta}\left(D_i^o(\underline{t})^2 - D_i^o(\bar{t},\bar{t};R)^2\right) + \\
&\quad +[p(1-R_i)(1-R_j)+1-p](\underline{\theta}+\phi(R))D_i^o(\bar{t},\bar{t};R)\frac{\partial D_i^o(\bar{t},\bar{t};R)}{\partial R_i} \\
&= \frac{p(1-R_j)[\phi(R)]^2W^2\left(\underline{\theta}\phi(R)+(\underline{\theta}+\Delta)(\underline{\theta}-2\Delta)\right)}{2(\underline{\theta}+\Delta)^2[\underline{\theta}+\phi(R)+\Delta]^3}, \\
MQ^o(R) &= p(1-R_j)W\left(D_j^o(\underline{t}) - D_j^o(\bar{t},\bar{t};R)\right) + \\
&\quad +[p(1-R_i)(1-R_j)+1-p]W\frac{\partial D_j^o(\bar{t},\bar{t};R)}{\partial R_i} \\
&= \frac{p(1-R_j)W^2[\phi(R)]^2}{(\underline{\theta}+\Delta)(\underline{\theta}+\phi(R)+\Delta)^2}.
\end{aligned}
$$

When we compare these expressions with expressions (3.4) and (3.6) we observe the following. Along the equilibrium path, when expectations are realized, $\widehat{D}_i = D_i^o$. Since observable changes in research investment affect own equilibrium development investments less than unobservable changes, we have $\widehat{MR}(R) < MR^o(R)$, for all R. It is therefore immediate that for the "winner-takes-all" race ($\sigma = 0$) observable equilibrium research investments are greater than unobservable equilibrium research investments for any cost of research investment ρ: $R_i^o(0) > \widehat{R}_i(0)$. But since observable changes in research investment do affect rival's equilibrium development investments, $\frac{\partial D_j^o(\bar{t},\bar{t};R)}{\partial R_i} < 0$, we have $\widehat{MQ}(R) > MQ^o(R)$, for all R. It is easily verified that in the "winner-takes-all" race firms with observable research investments still underinvest in research: $R_i^o(0) < \overline{R}_i$, for $i = 1, 2$.

For the "equal-sharing" race ($\sigma = \frac{1}{2}$) the effect of observable research investments on a firm's own as well as its rival's development investments are present. These effects point in opposing directions. Since the effect of observable research on own development investments is an indirect effect, while the effect on the rival's development investments is direct, the latter dominates the former in the "equal-sharing" race. This is reflected in the fact that for all R: $\widehat{MR}(R) + \widehat{MQ}(R) > MR^o(R) + MQ^o(R)$.[7] Therefore unobservable research investments exceed observable ones in equilibrium: $\widehat{R}_i(\frac{1}{2}) > R_i^o(\frac{1}{2})$, for $i = 1, 2$.

These results are summarized in the following proposition:

[7] It is easily verified that:

$$[\widehat{MR}(R) + \widehat{MQ}(R)] - [MR^o(R) + MQ^o(R)] = \frac{p(1-R_j)W^2\phi(R)(\underline{\theta}+\phi(R))}{(\underline{\theta}+\phi(R)+\Delta)^3} > 0.$$

Proposition 3.8 *Consider the race with public signals, and take $r_i = R_i$ for $i = 1, 2$. With observable research investments equilibrium is such that:*
(i.a) development investments do not differ: $\widehat{D}_i(t; R) = D_i^o(t; R)$, for all t, R,
(i.b) development investments fall more steeply in unobservable research investments than in observable ones: $\frac{\partial \widehat{D}_i(\bar{t},\bar{t};R)}{\partial R_i} < \frac{\partial D_i^o(\bar{t},\bar{t};R)}{\partial R_i} \leq 0$,
(ii) observable equilibrium research investments exceed unobservable ones in the "winner-takes-all" race, $R_i^o(0) \geq \widehat{R}_i(0)$, while the reverse holds in the "equal-sharing" race, $R_i^o(\frac{1}{2}) \leq \widehat{R}_i(\frac{1}{2})$. Where strict inequalities hold for interior equilibrium research investments.

We conclude that observable research investments create an effect on the way both firms respond to changes in research investments. The direction in which this effect points depends on the direction in which spillovers between firms point. In a setting where Cournot competitors acquire private information on their demand intercept, Hauk and Hurkens (1998) show that observable research investments exceed unobservable investments in equilibrium. The analysis of this subsection suggests that this conclusion is sensitive to their assumption on the kind of information that is acquired. Our analysis could be interpreted as one of Cournot competitors who acquire public information about the "slope of demand", and give different equilibrium results.[8]

3.8 Conclusion

In this chapter we studied investment incentives of firms who learn about the R&D project they work on, while they invest in it. We showed that these incentives are such that firms' pessimism grows when they receive bad news after more investments. This depresses development investments after bad signals are received. In a winner-takes-all race with public signals the firms overinvest in product development, because research efforts are duplicated. They underinvest in information acquisition, due to the public good nature of the disclosed information.

The chapter has demonstrated that firms' incentives change drastically when firms share revenues. When we introduce revenue sharing in the race with public signals, both research underinvestment and the development overinvestments are initially reduced. This suggests that firms would be better off if they would share revenues from

[8]Malueg and Tsutsui (1996) show that incentives to commit to sharing exogenous information change too when they move from information about unknown demand intercept to information about unknown slope. (Firms have a bigger incentive to share information about unknown slope.)

innovation. Revenue sharing should, however, not be driven too far. For example, in an equal-share R&D race firms underinvest both in information acquisition and development, due to free-rider incentives. An efficient revenue share trades off distortions of incentives in information acquisition and development of the innovation, and creates a race between "winner-take-all" and "equal-sharing".

Not only the extent to which firms share revenues, but also the observability of intermediate research results affects investment incentives substantially. When signals are private and firms acquire the same information, firms invest more in development along the equilibrium path. When firms receive different information, then the total development investment under public information exceeds that under private information. Again revenue sharing decreases firms' development incentives. Because free-rider effects are absent in a race with private signals, firms invest more in acquiring private than in public information when no revenues are shared. In contrast to the race with public signals, equilibrium investments in private signals decrease monotonically in the revenue share.

We have shown that the verifiability of intermediate research results is crucial in determining what kind of investments are actually made in equilibrium. No information is credibly revealed for any share of revenues when information is non-verifiable. In that case revealing no information is an equilibrium strategy. Therefore the research and development investments of the race with private signals are equilibrium investments for a race in which non-verifiable intermediate information is created. When firms' private information is verifiable, the "unraveling result" ensures for extreme revenue shares full disclosure of research results, and gives the public signal equilibrium investments. For intermediate revenue shares verifiable information will not be disclosed.

Observable research investments create more spillovers between firms' research investments, since changes in one firm's research investments affects both firms' posterior beliefs about their project. When an extra unit of research did not give an improvement in signal, both firms become more pessimistic about their project. This puts the investing firm in a relatively better position at the start of the development stage, as compared to a race with unobservable research investments. Therefore firms invest more in observable research than in unobservable research in the "winner-takes-all" race. When firms share revenues equally, a firm's growing pessimism from his rival's unsuccessful research investments is not beneficial for the rival. Therefore firms invest less in observable research in an equilibrium of the "equal-sharing" race.

Although we made a substantial first step in the analysis of learning effects in R&D races, there remain some open questions. It would be interesting to study the overall effect of the interaction between research and development investments by characterizing the expected equilibrium development investments given equilibrium research investments. The ultimate goal of this research project would be to make an overall comparison between expected profit levels under public and private signals. It would improve the paper if we could prove statements on partial information revelation in equilibrium. Also comparative statics would improve our understanding of the results. These, and other extensions of the analysis await future research.

3.9 Appendix

In this Appendix we prove the main propositions of this chapter. The first subsection proves the main propositions on equilibrium investments for public signals. Subsection 2 proves the main proposition for a race with private signals. In subsection 3 we prove the lemmas and propositions concerning strategic information revelation.

3.9.1 Proofs for Public Signal Race

In this subsection we prove propositions 3.1 and 3.3.

Proof of Proposition 3.1 ($\widehat{R} > \overline{R}$)

First we show that marginal revenues of research investments in the optimum are strictly larger than those in the public signal race:

$$\frac{p(1-R_j)W^2\phi(R)^2}{(\underline{\theta}+2\Delta)(\underline{\theta}+\phi(R)+2\Delta)^2} > \frac{p(1-R_j)W^2\phi(R)\left(\frac{1}{2}\underline{\theta}\phi(R)-\Delta(\underline{\theta}+\Delta)\right)}{(\underline{\theta}+\Delta)^2(\underline{\theta}+\phi(R)+\Delta)^2},$$

which certainly holds whenever:

$$\frac{1}{(\underline{\theta}+2\Delta)(\underline{\theta}+\phi(R)+2\Delta)^2} > \frac{\frac{1}{2}\underline{\theta}}{(\underline{\theta}+\Delta)^2(\underline{\theta}+\phi(R)+\Delta)^2} \Leftrightarrow$$

$$(\underline{\theta}+\Delta)^2(\underline{\theta}+\phi(R)+\Delta)^2 > \frac{1}{2}\underline{\theta}(\underline{\theta}+2\Delta)(\underline{\theta}+\phi(R)+2\Delta)^2 \quad \Leftrightarrow$$

$$\phi(R)^2(2\Delta^2+2\underline{\theta}\Delta+\underline{\theta}^2)+2\phi(R)(2\Delta^3+2\underline{\theta}\Delta^2+2\underline{\theta}^2\Delta+\underline{\theta}^3)+$$
$$+(2\Delta^4+2\Delta\underline{\theta}^3+\underline{\theta}^4)>0,$$

which obviously holds. Since marginal costs are identical, this gives underinvestments in research by competing firms.

Proof of Proposition 3.3 ($\partial\widehat{R}/\partial\sigma$)

For positive "winner-takes-all" research investments, i.e. $\widehat{MR}(R) > 0$, we apply the implicit function theorem to first-order condition (3.5) to derive that:

$$\frac{\partial \widehat{R}_i(\sigma)}{\partial \sigma} = \left.\frac{(1-2\sigma)\left(\widehat{MQ}(R) - \widehat{MR}(R)\right) - \widehat{MR}(R)}{(1-\sigma)\left((1-\sigma)\widehat{MR}'(R) + \sigma\widehat{MQ}'(R)\right) - \rho}\right|_{R=\widehat{R}(\sigma)},$$

Note that for an interior solution $\widehat{R}_i(\sigma)$, the second-order condition gives a non-negative denominator. The numerator is linear in prize share σ. For $\sigma = 0$ we obtain:

$$\frac{\partial \widehat{R}_i(0)}{\partial \sigma} = \left.\frac{\widehat{MQ}(R) - 2\widehat{MR}(R)}{\widehat{MR}'(R) - \rho}\right|_{R=\widehat{R}} > 0,$$

since $\widehat{MQ}(R) > 2\widehat{MR}(R)$ for all R, and therefore also for $\widehat{R}$. For $\sigma = \frac{1}{2}$ we get:

$$\frac{\partial \widehat{R}_i(\frac{1}{2})}{\partial \sigma} = \left.\frac{-\widehat{MR}(R)}{\frac{1}{4}\left(\widehat{MQ}'(R) + \widehat{MQ}'(R)\right) - \rho}\right|_{R=\widehat{R}(\frac{1}{2})} < 0,$$

because $\widehat{MR}(R) > 0$. From the linearity of the numerator we deduce that there always is a $\widehat{\sigma} \in (0, \frac{1}{2})$ such that $\frac{\partial \widehat{R}_i(\widehat{\sigma})}{\partial \sigma} = 0$.

3.9.2 Proof for Private Signal Race

In this subsection of the Appendix we prove proposition 3.5 and 3.4.

Proof of Proposition 3.4 ($D_i^*(.)$)

In part (i) the first inequality is obvious, while the second, for $r_i = R_i = R$ and $i = 1, 2$, reduces to:

$$\frac{\partial D_i^*(\bar{t}; R)}{\partial R_i} = \frac{-p(1-pR)\varphi(R_i)D_i^*(\bar{t}; R) + p(1-p)R\Delta\left(D_i^*(\underline{t}) - D_i^*(\bar{t}; R)\right)}{(1-pR)^2\left(\underline{\theta} + \varphi(R_i)\right)},$$

where the numerator is proportional to:

$$\begin{aligned} & -(1-pR)\varphi(R)[\underline{\theta} + \varphi(R) + (R - P(R))\Delta] + (1-p)R\varphi(R)\Delta \\ = \; & -(1-pR)\varphi(R)[\underline{\theta} + \varphi(R)], \end{aligned}$$

which is negative for $R < 1$.

For part (ii) it suffices to observe that:

$$D_i^*(\underline{t}; R) - \widehat{D}_i(\underline{t}) = \frac{(1-\sigma)(1-R)\Delta\varphi(R)W}{[(\underline{\theta}+R\Delta)(\underline{\theta}+\varphi(R)+(1-P(R))\Delta)-(1-R)P(R)\Delta^2](\underline{\theta}+\Delta)},$$

and

$$\begin{aligned}&D_i^*(\bar{t}; R) - \widehat{D}_i(\bar{t},\bar{t}; R) = \\ &\frac{(1-\sigma)\underline{\theta}[\phi(R)-\varphi(R)]W}{[(\underline{\theta}+R\Delta)(\underline{\theta}+\varphi(R)+(1-P(R))\Delta)-(1-R)P(R)\Delta^2](\underline{\theta}+\phi(R)+\Delta)},\end{aligned}$$

which obviously exceeds zero for $R < 1$. This completes the proof.

Proof of Proposition 3.5 ($R_i^*(0) \geq \widehat{R}_i(0)$)

In this proof we compare marginal research revenues for public signals with those for private signals. Naturally, from (3.4) we obtain:

$$\begin{aligned}\widehat{MR}(R) &< \frac{\frac{1}{2}p\underline{\theta}\phi(R)^2W^2}{(\underline{\theta}+\Delta)^2(\underline{\theta}+\phi(R)+\Delta)^2} \\ &= \frac{\frac{1}{2}p\underline{\theta}(1-p)^2(\overline{\theta}-\underline{\theta})^2W^2}{[p(1-R)^2+1-p]^2(\underline{\theta}+\Delta)^2(\underline{\theta}+\phi(R)+\Delta)^2}.\end{aligned} \tag{3.8}$$

For $\sigma = 0$ (3.7) marginal research revenues for private signals reduce to:

$$\begin{aligned}MR^*(R) &\equiv \frac{\frac{1}{2}p\underline{\theta}\varphi(R)^2W^2}{((\underline{\theta}+R\Delta)(\underline{\theta}+\varphi(R)+(1-P(R))\Delta)-(1-R)P(R)\Delta^2)^2} \\ &= \frac{\frac{1}{2}p\underline{\theta}(1-p)^2(\overline{\theta}-\underline{\theta})^2W^2}{(1-pR)^2((\underline{\theta}+R\Delta)(\underline{\theta}+\varphi(R)+(1-P(R))\Delta)-(1-R)P(R)\Delta^2)^2}\end{aligned} \tag{3.9}$$

When we compare denominators of (3.8) and (3.9), we obtain:

$$\begin{aligned}&[p(1-R)^2+1-p](\underline{\theta}+\Delta)(\underline{\theta}+\phi(R)+\Delta)+ \\ &-(1-pR)\left((\underline{\theta}+R\Delta)(\underline{\theta}+\varphi(R)+(1-P(R))\Delta)-(1-R)P(R)\Delta^2\right) \\ = \;&(E(\theta)+\Delta)[2\underline{\theta}+(1+R)\Delta]-pR(3-R)(\underline{\theta}+\Delta)^2.\end{aligned}$$

Since this expression is linear and decreasing in p it suffices to evaluate it for $p = 1$. For $p = 1$ the expression reduces to:

$$(1-R)(\underline{\theta}+\Delta)[\underline{\theta}+(1-R)(\underline{\theta}+\Delta)] \geq 0.$$

This implies that $\widehat{MR}(R) < MR^*(R)$ for all $R < 1$, which completes the proof.

3.9.3 Proofs for Strategic Revelation

In this subsection we prove lemma 3.6, propositions 3.4 and 3.7.

Proof of Proposition 3.6 (No Complete Revelation)

Suppose complete revelation does happen in equilibrium. Then equilibrium beliefs are such that any statement is believed. Firm j's equilibrium investments would be $\widehat{D}_j(\underline{t}) = \frac{(1-\sigma)W}{\underline{\theta}+\Delta}$ and $\widehat{D}_j(\bar{t},\bar{t}) = \frac{(1-\sigma)W}{\underline{\theta}+\phi(r)+\Delta} \cdot \frac{\underline{\theta}+\phi(r)}{\underline{\theta}+\phi(R_i,r_j)}$, respectively. Suppose that firm j completely reveals his information, and that he received signal $t_j = \bar{t}$ from nature. Then if firm i received signal $\underline{t}$ and reveals it, firms invest $\widehat{D}(\underline{t})$, and firm i has expected profit:

$$\pi_i(\underline{t}|\underline{t}) = (1-\sigma)W^2 \frac{(1-\sigma)\frac{1}{2}\underline{\theta} + \sigma(\underline{\theta}+\Delta)}{(\underline{\theta}+\Delta)^2}.$$

If firm i states $\bar{t}$ instead, this makes firm j invest $\widehat{D}_j(\bar{t},\bar{t})$. Firm i's optimal response to $\widehat{D}_j(\bar{t},\bar{t})$ is $D_i = \frac{(1-\sigma)W(\underline{\theta}+\phi(r))}{(\underline{\theta}+\phi(r)+\Delta)\underline{\theta}}$. Firm i's profit from overstating his signal is:

$$\pi_i(\bar{t}|\underline{t}) = (1-\sigma)W^2 \frac{(1-\sigma)\frac{1}{2}(\underline{\theta}+\phi(r))^2 + \sigma\underline{\theta}(\underline{\theta}+\phi(r)+\Delta)}{\underline{\theta}(\underline{\theta}+\phi(r)+\Delta)^2}.$$

The difference in profit between overstating and truth-telling is:

$$\pi_i(\bar{t}|\underline{t}) - \pi_i(\underline{t}|\underline{t}) = \frac{(1-\sigma)W^2}{\underline{\theta}(\underline{\theta}+\Delta)^2(\underline{\theta}+\phi(r)+\Delta)^2}\left((1-\sigma)a + \sigma(-b)\right),$$

with

$$\begin{aligned} a &\equiv \frac{1}{2}\left([(\underline{\theta}+\phi(r))(\underline{\theta}+\Delta)]^2 - [\underline{\theta}(\underline{\theta}+\phi(r)+\Delta)]^2\right), \\ b &\equiv \underline{\theta}(\underline{\theta}+\Delta)(\underline{\theta}+\phi(r)+\Delta)\phi(r). \end{aligned}$$

Hence, there is a $\underline{\sigma} \in (0,1)$ such that $\pi_i(\bar{t}|\underline{t}) > \pi_i(\underline{t}|\underline{t})$ iff $\sigma \leq \underline{\sigma}$. Similar for a $\bar{t}$-firm i, stating $\underline{t}$ (resp. $\bar{t}$) makes $\bar{t}$-firm j choose $\widehat{D}_j(\underline{t})$ (resp. $\widehat{D}_j(\bar{t},\bar{t})$). Firm i's optimal response to this investment is $D_i = \frac{(1-\sigma)W\underline{\theta}}{(\underline{\theta}+\Delta)(\underline{\theta}+\phi(R_i,r_j))}$ (resp. $\widehat{D}_i(\bar{t},\bar{t})$). Firm i's profit for understating its signal is:

$$\pi_i(\underline{t}|\bar{t}) = (1-\sigma)W^2 \frac{(1-\sigma)\frac{1}{2}\underline{\theta}^2 + \sigma(\underline{\theta}+\Delta)(\underline{\theta}+\phi(R_i,r_j))}{(\underline{\theta}+\Delta)^2(\underline{\theta}+\phi(R_i,r_j))},$$

while truth-telling gives it:

$$\pi_i(\bar{t}|\bar{t}) = (1-\sigma)W^2 \frac{(1-\sigma)\frac{1}{2}(\underline{\theta}+\phi(r))^2 + \sigma(\underline{\theta}+\phi(r)+\Delta)(\underline{\theta}+\phi(R_i,r_j))}{(\underline{\theta}+\phi(r)+\Delta)^2(\underline{\theta}+\phi(R_i,r_j))}.$$

The difference in profit between understating and truth-telling is:

$$\pi_i(\underline{t}|\overline{t}) - \pi_i(\overline{t}|\overline{t}) = \frac{(1-\sigma)W^2}{(\underline{\theta}+\Delta)^2(\underline{\theta}+\phi(r)+\Delta)^2(\underline{\theta}+\phi(R_i,r_j))}\left((1-\sigma)(-A)+\sigma B\right),$$

with

$$A \equiv a, \text{ and } B = (\underline{\theta}+\phi(R_i,r_j))(\underline{\theta}+\Delta)(\underline{\theta}+\phi(r)+\Delta)\phi(r).$$

Hence, there is a $\overline{\sigma} \in (0,1)$ such that $\pi_i(\underline{t}|\overline{t}) \geq \pi_i(\overline{t}|\overline{t})$ whenever $\sigma \geq \overline{\sigma}$. It is straightforward that $b \leq B$. This implies that $\overline{\sigma} \leq \underline{\sigma}$, and, thus, is deviating from complete revelation profitable for all $\sigma \in [0,1]$. This completes the proof.

Proof of Lemma 3.4 (No Revelation)

Observe that when firms never update their beliefs, each firm is indifferent between all revelation rules, i.e. $\pi_i(\tau_i(t_i),\tau_j) = \pi_i(\tau_i'(t_i),\tau_j) = E_\theta\{\pi_i(D^*;\theta)|t_i;R_i\}$ for all τ_i,τ_i' and τ_j. No revelation, e.g. $\widehat{\tau}_i(t_i) = \underline{t}$ for $i=1,2$, is therefore weakly preferred by firms, which is consistent with beliefs. By stating high costs, no type of firm i can obtain higher profits, since beliefs are not updated.

Proof of Proposition 3.7 (Verifiable Information)

Since information is verifiable, a firm can only choose to either disclose or conceal its signal, $\tau_i(t_i) \in \{t_i, \varnothing\}$. If only one type of firm chooses to conceal its signal, its rival can infer its information perfectly. We therefore only need to distinguish between strategies of full disclosure and full concealment. We take $\overline{\sigma}$, $\underline{\sigma}$, and $\pi_i(.|.)$ as in the proof to lemma 3.6, and characterize part (i), (ii) and (iii), respectively.
(i) Take $\sigma \leq \overline{\sigma}$. Suppose that firm j discloses its information: $\tau_j(t_j) = t_j$ for $t_j \in \{\underline{t},\overline{t}\}$. In that case firm i's disclosure rule can only affect the equilibrium outcome when firm j discloses $\overline{t}$. Firm i's expected profit from disclosing private signals $\underline{t}$ and $\overline{t}$ is then $\pi_i(\underline{t}|\underline{t})$ and $\pi_i(\overline{t}|\overline{t})$, respectively. Suppose that firm i deviates from complete revelation and conceals its signal. After concealment firm j updates its beliefs skeptically, and believes that $t_i = \underline{t}$ with probability 1, i.e. $\pi_i(\varnothing|t_i) \equiv \pi_i(\underline{t}|t_i)$. Consequently it invests $\widehat{D}_j(\underline{t})$ in development. This leaves firm i indifferent between disclosing and concealing when $t_i = \underline{t}$. When firm i has private signal $\overline{t}$, it prefers to disclose his signal, since $\pi_i(\overline{t}|\overline{t}) \geq \pi_i(\underline{t}|\overline{t})$ iff $\sigma \leq \overline{\sigma}$. Hence sceptical beliefs are consistent with firm's incentives, and firms' disclosure strategies are optimal given beliefs.

(ii) Take $\overline{\sigma} < \sigma < \underline{\sigma}$, and suppose that firm j discloses his information. Firm j's development investments can only be affected by firm i's disclosure decision when firm j receives a bad signal, $t_j = \overline{t}$. We consider this case. After firm i's concealment, $\widetilde{\tau}_i = \varnothing$, firm j assigns probability μ to the contingency that firm i received a good signal, $t_i = \underline{t}$, with $0 \leq \mu \leq 1$. Firm j's expected costs of development after concealment are $\underline{\theta} + (1-\mu)\phi(r_i, R_j)$. The first-order condition for firm j's investments is the following:

$$(\underline{\theta} + (1-\mu)\phi(r_i, R_j))D_j(\varnothing; R_j) = (1-\sigma)W - \left(\mu D_i(\underline{t}) + (1-\mu)D_i(\overline{t})\right)\Delta.$$

Firm i's first-order conditions remain unchanged. Given firm j's belief, we obtain the following equilibrium investments:

$$\begin{aligned}
D_j^{\mu}(\varnothing; r_j) &= \frac{(1-\sigma)W\left[\underline{\theta}(\underline{\theta}+\phi(r)) - (\underline{\theta}+\mu\phi(r))\Delta\right]}{\underline{\theta}(\underline{\theta}+\phi(r))(\underline{\theta}+(1-\mu)\phi(r)) - (\underline{\theta}+\mu\phi(r))\Delta^2} \\
D_i^{\mu}(\underline{t}) &= \frac{(1-\sigma)W(\underline{\theta}+\phi(r))(\underline{\theta}+(1-\mu)\phi(r)-\Delta)}{\underline{\theta}(\underline{\theta}+\phi(r))(\underline{\theta}+(1-\mu)\phi(r)) - (\underline{\theta}+\mu\phi(r))\Delta^2} \\
D_i^{\mu}(\overline{t}; R_i) &= \frac{(1-\sigma)W\underline{\theta}(\underline{\theta}+(1-\mu)\phi(r)-\Delta)}{\underline{\theta}(\underline{\theta}+\phi(r))(\underline{\theta}+(1-\mu)\phi(r)) - (\underline{\theta}+\mu\phi(r))\Delta^2} \cdot \frac{(\underline{\theta}+\phi(r))}{(\underline{\theta}+\phi(R_i, r_j))}.
\end{aligned}$$

Firm i's expected equilibrium profits are:

$$\begin{aligned}
\pi_i^{\mu}(\varnothing|\underline{t}) &= \frac{1}{2}\underline{\theta} D_i^{\mu}(\underline{t})^2 + \sigma W D_j^{\mu}(\varnothing; r_j) \\
\pi_i^{\mu}(\varnothing|\overline{t}) &= \frac{1}{2}(\underline{\theta}+\phi(R_i, r_j))D_i^{\mu}(\overline{t}; R_i)^2 + \sigma W D_j^{\mu}(\varnothing; r_j)
\end{aligned}$$

Note that for belief $\mu = 0$ firm i strictly prefers to conceal $\underline{t}$, since $\pi_i^0(\varnothing|\underline{t}) = \pi_i(\overline{t}|\underline{t}) > \pi_i(\underline{t}|\underline{t})$ for $\sigma < \underline{\sigma}$. We can therefore rule out belief $\mu = 0$ as supporting a full disclosure equilibrium. Belief $\mu = 1$ can be ruled out too, because firm i prefers to conceal a bad signal given this belief, i.e. $\pi_i^1(\varnothing|\overline{t}) = \pi_i(\underline{t}|\overline{t}) > \pi_i(\overline{t}|\overline{t})$ for $\sigma > \overline{\sigma}$. For beliefs strictly between 0 and 1 there is a critical value $\underline{\sigma}^{\mu}$ (resp. $\overline{\sigma}^{\mu}$) such that disclosing $\underline{t}$ (resp. $\overline{t}$) is profitable for firm i whenever $\sigma \geq \underline{\sigma}^{\mu}$ (resp. $\sigma \leq \overline{\sigma}^{\mu}$). The critical values are defined as follows:

$$\begin{aligned}
\underline{\sigma}^{\mu} &= \frac{\frac{1}{2}\underline{\theta}\left(d_i^{\mu}(\underline{t})^2 - \widehat{d}_i(\underline{t})^2\right)}{\frac{1}{2}\underline{\theta}\left(d_i^{\mu}(\underline{t})^2 - \widehat{d}_i(\underline{t})^2\right) - \left(d_j^{\mu}(\varnothing; r_j) - \widehat{d}_j(\underline{t})\right)}, \text{ and} \\
\overline{\sigma}^{\mu} &= \frac{-\frac{1}{2}(\underline{\theta}+\phi(R_i, r_j))\left(d_i^{\mu}(\overline{t}; R_i)^2 - \widehat{d}_i(\overline{t}; R_i)^2\right)}{-\frac{1}{2}(\underline{\theta}+\phi(R_i, r_j))\left(d_i^{\mu}(\overline{t}; R_i)^2 - \widehat{d}_i(\overline{t}; R_i)^2\right) + \left(d_j^{\mu}(\varnothing; r_j) - \widehat{d}_j(\overline{t}; r_j)\right)},
\end{aligned}$$

where $d_\ell(.) \equiv D_\ell(.)/(1-\sigma)W$, with $\ell = i, j$. For prize share σ full disclosure is an equilibrium strategy given belief μ, whenever belief μ is such that $\underline{\sigma}^{\mu} \leq \sigma \leq \overline{\sigma}^{\mu}$. First we verify that both $\underline{\sigma}^\mu$ and $\overline{\sigma}^\mu$are monotonically decreasing in belief μ for $0 < \mu < 1$:

$$\frac{\partial \underline{\sigma}^\mu}{\partial \mu} = \frac{\underline{\theta}\left[\frac{1}{2}\frac{\partial d_j^\mu(\varnothing;r_j)}{\partial \mu}\left(d_i^\mu(\underline{t})^2 - \widehat{d}_i(\underline{t})^2\right) - d_i^\mu(\underline{t})\frac{\partial d_i^\mu(\underline{t})}{\partial \mu}\left(d_j^\mu(\varnothing;r_j) - \widehat{d}_j(\underline{t})\right)\right]}{\left[\frac{1}{2}\underline{\theta}\left(d_i^\mu(\underline{t})^2 - \widehat{d}_i(\underline{t})^2\right) - \left(d_j^\mu(\varnothing;r_j) - \widehat{d}_j(\underline{t})\right)\right]^2}$$

$$= \frac{\frac{-(1-\mu)^2\frac{1}{2}\underline{\theta}^2\phi(r)^3\Delta^2(\underline{\theta}+\phi(r))(\underline{\theta}+\phi(r)-\Delta)^3(\underline{\theta}-\Delta)}{(\underline{\theta}+\Delta)^2[\underline{\theta}(\underline{\theta}+\phi(r))(\underline{\theta}+(1-\mu)\phi(r))-(\underline{\theta}+\mu\phi(r))\Delta^2]^4}}{\left[\frac{1}{2}\underline{\theta}\left(d_i^\mu(\underline{t})^2 - \widehat{d}_i(\underline{t})^2\right) - \left(d_j^\mu(\varnothing;r_j) - \widehat{d}_j(\underline{t})\right)\right]^2} < 0, \text{ and}$$

$$\frac{\partial \overline{\sigma}^\mu}{\partial \mu} = \frac{(\underline{\theta}+\phi(R_i,r_j))\left[\begin{array}{c}\frac{1}{2}\frac{\partial d_j^\mu(\varnothing;r_j)}{\partial \mu}\left(d_i^\mu(\overline{t};R_i)^2 - \widehat{d}_i(\overline{t};R_i)^2\right) + \\ -d_i^\mu(\overline{t};R_i)\frac{\partial d_i^\mu(\overline{t};R_i)}{\partial \mu}\left(d_j^\mu(\varnothing;r_j) - \widehat{d}_j(\overline{t};r_j)\right)\end{array}\right]}{\left[\frac{1}{2}\underline{\theta}\left(d_i^\mu(\overline{t};R_i)^2 - \widehat{d}_i(\overline{t};R_i)^2\right) - \left(d_j^\mu(\varnothing;r_j) - \widehat{d}_j(\overline{t};R_i)\right)\right]^2}$$

$$= \frac{\frac{-\mu^2\frac{1}{2}\underline{\theta}\phi(r)^3\Delta^2(\underline{\theta}+\phi(r))(\underline{\theta}+\phi(r)-\Delta)(\underline{\theta}-\Delta)^3}{(\underline{\theta}+\phi(r)+\Delta)^2[\underline{\theta}(\underline{\theta}+\phi(r))(\underline{\theta}+(1-\mu)\phi(r))-(\underline{\theta}+\mu\phi(r))\Delta^2]^4}\cdot\frac{(\underline{\theta}+\phi(r))^2}{(\underline{\theta}+\phi(R_i,r_j))}}{\left[\frac{1}{2}\underline{\theta}\left(d_i^\mu(\overline{t};R_i)^2 - \widehat{d}_i(\overline{t};R_i)^2\right) - \left(d_j^\mu(\varnothing;r_j) - \widehat{d}_j(\overline{t};R_i)\right)\right]^2} < 0.$$

Furthermore, it is easily verified that:

$$\lim_{\mu\uparrow 1}\underline{\sigma}^\mu = \frac{\Delta}{\underline{\theta}+2\Delta} > \frac{\Delta}{\underline{\theta}+\phi(r)+2\Delta} = \lim_{\mu\downarrow 0}\overline{\sigma}^\mu.$$

In combination with monotonicity this implies that $\underline{\sigma}^\mu > \overline{\sigma}^\mu$ for all $0 < \mu < 1$. Therefore there is no belief μ such that full disclosure is chosen in equilibrium.

(iii) For $\sigma \geq \underline{\sigma}$ we have a similar argument as in (i). Sceptical beliefs after concealment are to believe that your rival has a "bad" signal, i.e. $\pi_i(\varnothing|t_i) \equiv \pi_i(\overline{t}|t_i)$. This leaves firm i with a bad signal indifferent between disclosing and concealing. Firm i with a good signal is worse off by concealing its signal, since $\pi_i(\overline{t}|\underline{t}) \leq \pi_i(\underline{t}|\underline{t})$ iff $\sigma \geq \underline{\sigma}$. This completes the proof.

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Chapter 4

Disclosure Regulation and Correlation

4.1 Introduction

A basic property of research and development (R&D) is that it generates information for the firms who invest in it. Usually this information is private to the firms and is produced along the trajectory of the R&D project that leads to an innovation. Disclosure or concealment by competing research labs of such intermediate information can have different effects on R&D competition. This gives these labs different incentives to disclose information, and consequently different incentives to invest in the creation of information and in the development of the innovation. This chapter discusses in what direction the different incentives point and what investments result from it.

For some innovations firms aggressively preannounce their new products to discourage rivals. For example, in the operating system market many people claim that Microsoft (MS) is using preannouncements of its operating system upgrades to drive competition out of their market.[1] Such a preannouncement strategy is called a "vaporware" strategy. On many occasions MS is accused of practicing such an aggressive preannouncement strategy. Disclosing good news about their own capabilities of introducing a new product in the market quickly, discourages rivals to invest in the development of competing products. In most literature on dynamic R&D competition the progress of one firm in their project discourages his rivals to invest in the innovation. Taking a lead in the race gives the leading firm a strategic advantage, e.g. see Grossman and Shapiro (1987), and Harris and Vickers (1987). This is a "strategic

[1]See e.g. Lopatka and Page (1995), Prentice (1996), Shapiro (1996), United States v. Microsoft, Civil Action No. 94-1564, and Shapiro and Varian (1999). An extensive anacdotical report on Microsoft's strategies is presented in Wallace and Erickson (1992).

effect". If firms can disclose that they made an early intermediate discovery without revealing the contents of this discovery, they would always do so.[2]

The strategic effect can be observed in another case. British Biotech (BB) is a pharmaceutical firm whose main activity is research on and development of anti-cancer drugs. In the Spring of 1998 director of clinical research Andrew Millar of BB was dismissed after disclosing bad news about BB's research and commercial strategy. As a result of the disclosure BB's stock market value collapsed, reflecting its reduced opportunities in the race for anti-cancer drugs. By concealing their bad test results, the firm tried to keep the market optimistic about its capabilities of introducing a new drug shortly.[3] Both cases suggest the predominance of the strategic effect of information disclosure. From the disclosed information rival firms learn about the firm's progress in the race, and become more pessimistic about their own opportunities of participating in the R&D race. Disclosing good news, and concealing bad news about yourself makes your rivals believe that you will be a strong competitor in the remainder of the race.

Although the effects of information disclosure and concealment are similar in the two cases, regulatory responses differed substantially. In the 1994-95 licencing court case against Microsoft Corp., Microsoft's "vaporware" practices where investigated (e.g. see US v MS, 1995). This did not lead to any restrictive regulation of Microsoft's announcements. Regulations in the pharmaceutical industry, however, require firms to disclose their intermediate testing results. The attempted concealment by British Biotech had severe negative consequences for its chances to get approval from the European Medical Evaluation Agency (EMEA) to sell developed drugs. In this chapter we study the effects of regulating firms' disclosure strategies. We compare firms' investments and profits under a regime of mandated disclosure with those under voluntary disclosure.

In other industries we can observe an effect of intermediate information disclosure that conflicts with the strategic effect. For fundamental innovations, for which firms do not have a clear idea of their costs of investment, disclosure of intermediate successes can encourage rival firms to invest. An example of this type of behavior

[2]In patenting the preannouncement is accompanied with disclosure of the contents of the intermediate innovation. Typically patents trade off the benefit (from catching up of firms) against the cost (from free-riding on competitors' research efforts) of information appropriation. For dynamic incentives of patents, see e.g. Scotchmer and Green (1990), and Green and Scotchmer (1995).

[3]For coverage on this case, e.g. see *Financial Times* April 21, 27, and their survey at May 2/3 1998.

is provided by the history of the development of cold superconductivity.[4] Here one firm's intermediate success gives not only an indication of this firm's capabilities of developing the new product, but also of that of its rivals. After an early intermediate success by one firm, rivals flock in and invest to obtain the final innovation first. This effect could be explained in the following setting, as in Choi (1991). Firms learn about the properties of their project while they work on it. These properties are universal for the industry. Favorable information for one firm is favorable also for its rivals. Then progressing in the race and disclosing this progress makes all firms more optimistic, and more willing to invest. This is an "informational effect". But when favorable information for one firm also encourages rivals to invest in the project, the firm might want to prevent its rivals from learning this information. Such an informational effect would induce firms to conceal good news about their research progress, and disclose only bad news. Concealing good news and disclosing bad news makes your rivals believe that the project has high costs of investment, which discourages their investments.

Note that the strategic and informational effect lead to conflicting incentives to disclose preliminary information about one's costs of investment. The interaction between the two effects is studied in this chapter. R&D races are typically dynamic processes in which firms learn in the course of investing in it. Information is actively and endogenously acquired in R&D races. Information need not always flow freely between firms. In many situations firms actively manage the flow of information that they generate. This adds a new dimension to the firms' strategies. The main contribution of this chapter is that it provides a theory on firms' incentives to strategically disclose endogenous information to rivals. The trade-off between the incentives to create, disclose and further build upon information in an R&D race is analyzed in this chapter. As far as I know has this never been done in the literature. Furthermore we discuss the consequences of disclosure regulation for firms' investments and expected profits. We distinguish between the policy of mandated and voluntary disclosure, and study their consequences for firms' investments and profits.

When correlation between firms' costs of investments is positive, both the informational and strategic effect emerge after disclosure of information. For perfect positive correlation between costs of investments we show that the informational effect dominates the strategic effect in most cases. Firms disclose bad news, and conceal good news to make their rival as pessimistic about costs of investment as possible. There

[4] This example can be found in e.g. Choi (1991).

are, however, also special cases in which the strategic effect is more powerful. With independent costs the informational effect disappears. Since costs are independently distributed, one firm's cost disclosure doesn't affect the other firm's expected costs of investments. The strategic effect remains. Which suggests that firms disclose good news only. Disclosing good information and concealing bad information makes rivals expect strong competitors in the development stage, while it leaves their rival's own cost expectations unchanged. Note that the firms' equilibrium disclosure rule under independently distributed costs is in general exactly the opposite of that under perfect positive correlation. By focusing on these extreme cases we get a clear-cut trade-off between incentives to disclose and acquire information and to further develop the innovation.

Related literature: Races in which firms learn after investing are studied by Hendricks and Kovenock (1989), Choi (1991), Malueg and Tsutsui (1997), and Cyert and Kumar (1996). The first three papers assume that information flows freely between competing firms. And in Cyert and Kumar information becomes public after one of the firms starts producing the innovation. Katsoulacos and Ulph (1998) study R&D competition in which firms actively manage their information, but this information is exogenous.

"Vaporware", i.e. strategic preannouncement of good news and concealment of bad news, has been analyzed in some papers. One of the first papers to point to the potential strategic implications of preannouncements is Ordover and Willig (1981). In a seminal contribution by Farrell and Saloner (1986) the strategic effects of product preannouncements are mainly driven by consumers' myopia: consumers only anticipate a new product after the preannouncement of it. Both Levy (1997), and Lopatka and Page (1995) note that in a signalling setting preannouncements only have strategic effects when false announcements affect rival's or consumers' beliefs. Haan (1998) provides a signalling model of "vaporware" with intelligent consumers. False preannouncements do not affect consumers' beliefs and no information is revealed in equilibrium. A first step towards an empirical analysis of vaporware effects in the Digital Versatile Disc (DVD) player industry is made in Dranove and Gandal (1999). In this chapter we present the first model that I know of that results in strategic preannouncements among intelligent agents.

A powerful result in the theory of strategic disclosure of verifiable information is the "unraveling result". Seminal contributions by Grossman (1981), Milgrom (1981), Milgrom and Roberts (1986), and Okuno-Fujiwara *et al.* (1990) study this result. When it is known that the sender of information is informed, and information is costlessly verifiable, he cannot do better than disclose his information, given skeptical equilibrium beliefs of the receiver. This result relies on the assumptions that information is costlessly verifiable and that it is known that the sender is informed. Uncertainty about whether or not the sender is informed and non-verifiability of uninformedness disables the unraveling result in most cases. Austen-Smith (1994) shows that when the receiver is uncertain about the informedness of the sender, the sender can conceal some of his information in equilibrium. In equilibrium good news is disclosed while bad news is concealed from the receiver. This argument is generalized and refined by Shin (1994). Recently Krishnan *et al.* (1996) provide empirical evidence that firms partially disclose earnings information to the financial market. We will use a similar framework of uncertain informedness to study strategic disclosure by racing R&D laboratories.

The incentives to acquire and disclose information have been studied in firm-financial market (see Verecchia, 1990), buyer-seller (see Shavell, 1994) and lobbyist-government (see Lagerlöf, 1997) settings. These papers endogenize the degree of informedness of the sender, but abstract from competition between senders. Papers in which firms strategically disclose information under competition are Admati and Pfleiderer (1998), Dewatripont and Tirole (1999), and Shin (1998). The setup of these papers, however, is such that senders disclose or conceal information to a third party. Both Shavell (1994) and Admati and Pfleiderer (1998) are interested in the effects of disclosure regulation. This is a main theme of this chapter too.

Our contribution to the existing literature is twofold. First we endogenize the extent to which firms are uninformed, by allowing firms to acquire costly information. And second we study a problem in which competing firms disclose to each other. Disclosed information affects competition in developing the innovation. This means that we endogenize the costs and benefits of both information acquisition and disclosure. This is the main contribution of this chapter.

The chapter is organized as follows. In the next section of this chapter we describe the model. The third section discusses results under perfect positive correlation between firms' costs of development investments. We compare the benchmark outcome in which firms maximize joint profits, the equilibrium of the game for mandatory disclosure, and the equilibrium for voluntary disclosure of information. Section 4 gives results for identical independently distributed costs of development investments. The last section concludes the chapter.

4.2 The Model

Consider the simplest environment in which two firms compete over two stages for an innovation. At the beginning of the race firms do not know the complexity of their project, θ_i for firm i, with $i = 1, 2$. Firm i's project is either easy or tough. An easy project for firm i has low costs of development $\theta_i = \underline{\theta}$, while a tough project has high costs of development $\theta_i = \overline{\theta}$, with $0 < \underline{\theta} < \overline{\theta}$. The probability of working on an easy (resp. tough) project is p (resp. $1-p$), with $0 < p < 1$. Projects' costs of development investments are either perfectly positively correlated, or identically independently distributed. For $\Pr[\theta_1 = \theta_2 = \underline{\theta}] = p$ and $\Pr[\theta_1 = \theta_2 = \overline{\theta}] = 1 - p$, projects are perfectly positively correlated. We study the model with perfect positive correlation (PPC) in the next section of this chapter. For $\Pr[\theta_i = \underline{\theta}] = p$, $\Pr[\theta_i = \overline{\theta}] = 1 - p$ with θ_i and θ_j independent ($i \neq j$), projects are identically independently distributed (IID). This specification of the model is analyzed in the fourth section of this chapter.

Firms can learn about the complexity of their project by doing research in the first stage of the race. In this stage firms choose their research investments, $R_i \in [0, 1]$ for firm i, simultaneously. Research investments are not observable. Firm i's rival expects research investments r_i. Costs of research are strictly convex and increasing in investment: $c(R_i) = \frac{1}{2}\rho R_i^2$, with $\rho > 0$. The research stage leads to a prototype of the final innovation, and could provide information about the development costs.[5] After investing in research each firm receives a signal, Θ_i for firm i, about his cost of development. With probability R_i firm i learns its true cost of development, $\Theta_i = \theta_i$. However, with probability $1 - R_i$ firm i learns nothing, $\Theta_i = \varnothing$. Thus the more a firm invests in research, the sharper its signal on the project's complexity will be. The research stage is summarized in figure 4.1.

Information obtained by firms is verifiable. Only the fact whether or not a firm is informed is not verifiable. If firm i receives information θ_i, it can choose to either disclose it or conceal it, i.e. the firm chooses his communication $\delta_i(\theta_i)$ from the set $\{\theta_i, \varnothing\}$. An uninformed firm can only state $\delta_i(\varnothing) = \varnothing$. It therefore suffices to denote firm i's disclosure rule as $(\underline{\delta}_i, \overline{\delta}_i) \equiv (\delta_i(\underline{\theta}), \delta_i(\overline{\theta}))$. We denote the realization of rule $\delta_i(.)$ as $\widetilde{\delta}_i$, with $\widetilde{\delta}_i \in \{\delta_i(\Theta_i) | \Theta_i \in \{\underline{\theta}, \overline{\theta}, \varnothing\}\}$ for $i, j = 1, 2$ and $i \neq j$. That is, $\widetilde{\delta}_i$ is the message from firm i to j.

In the second stage firms invest in the development of their prototype by investing

[5] We assume that developing the prototype is a necessary step in successfully developing the innovation. The only reason for doing so is to avoid that firms decide not to acquire information and skip the first stage of the race in order to take a lead over their rival.

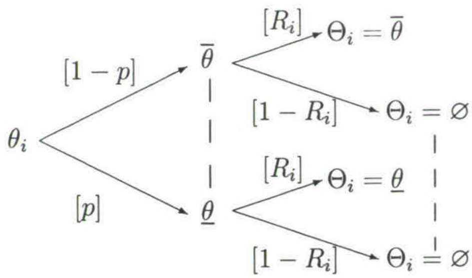

Figure 4.1: Firm i's research stage

D_i, with $D_i \in [0,1]$. Costs of development investment increase in investment and complexity: $C(D_i;\theta_i) = \frac{1}{2}\theta_i D_i^2$. With probability D_i firm i manages to develop a marketable product, with probability $1 - D_i$ it develops nothing. In this chapter we study a "winner-takes-all" race. A firm gets payoff W, when it is the only firm that develops the prototype. When both firms develop a marketable product, both firms get payoff T. When a firm does not manage to develop the prototype it gets no payoff. Naturally, we take $W \geq 2T \geq 0$. Define $\Delta \equiv W - T$ as the prize difference between winning and tying in the race. Because T is non-negative and cannot exceed $\frac{1}{2}W$, we obtain that $\frac{1}{2}W \leq \Delta \leq W$. For convenience we assume that $\underline{\theta} > 2\Delta$, since this enables us to focus on interior development investment solutions.

Firms are risk neutral. Given the projects' complexity, and sunk costs of research investments, firm i's expected development profit is:

$$\pi_i(D;\theta_i) = D_i(1-D_j)W + D_i D_j T - \frac{1}{2}\theta_i D_i^2 = D_i(W - D_j\Delta) - \frac{1}{2}\theta_i D_i^2,$$

with $D = (D_i, D_j)$. We solve the game backwards, and restrict the analysis to symmetric, pure strategy equilibria.

4.3 Perfect Positive Correlation (PPC)

In this section we assume that there is perfect positive correlation between firms' development costs. We choose $\Pr[\theta_1 = \theta_2 = \underline{\theta}] = p$ and $\Pr[\theta_1 = \theta_2 = \overline{\theta}] = 1 - p$. This reduces the firms' costs to $\theta_i = \theta$, with $\theta \in \{\underline{\theta}, \overline{\theta}\}$ and $i = 1, 2$. In the case of perfect positive correlation firms could learn about their own cost of development investment from their own acquired signal, and from disclosed information by their rival. The expected development cost parameter can therefore be denoted by

$\theta_i^E(\Theta_i, \widetilde{\delta}_j, \delta) \equiv E(\theta_i|\Theta_i, \widetilde{\delta}_j, \delta_j)$, for $i, j = 1, 2,\ i \neq j$. For example, when firm i is uninformed, $\Theta_i = \varnothing$, while it receives bad news about its rival, $\widetilde{\delta}_j = \overline{\theta}$, it does not only learn that it faces a high-cost rival, $\theta_j = \overline{\theta}$, but it also learns that its own costs of development investment are high, $\theta_i^E(\varnothing, \overline{\theta}, \delta) = \overline{\theta}$. This gives us the informational effect of information disclosure.

In the next subsection we solve for the industry's joint profit maximizing investments and disclosure rules. In the second subsection we derive and discuss firms' equilibrium investments under mandated disclosure. Finally we discuss the equilibrium investments and disclosure rules when firms voluntarily disclose information. All proofs are relegated to the Appendix.

4.3.1 Benchmark: Efficient Investments (PPC)

In this section we solve for the joint profit maximizing outcome of the race. We solve the game backwards. Note that for joint profits full disclosure is never worse than any other disclosure rule — firms can always choose to ignore certain disclosed information. It is therefore optimal to take $\delta_i(\Theta_i) \equiv \Theta_i$ for $i = 1, 2$.

Efficient Development Investments

In this subsection we derive the efficient development investments, given full information disclosure and any research investments. It is intuitive that firms' efficient development investments decreases in the expected cost of development, and increase in the prize that is at stake. We show this in the remainder of this subsection.

After acquiring and disclosing information we can distinguish between two cases. First, there are cases in which firms invest under complete information. Whenever one of the firms receives an informative signal about development cost, both firms are fully informed about their costs of development investment. The expected cost parameter equals:

$$\theta_i^E(\theta, \theta) = \theta_i^E(\theta, \varnothing) = \theta_i^E(\varnothing, \theta) = \theta, \text{ for } \theta \in \{\underline{\theta}, \overline{\theta}\} \text{ and } i = 1, 2.$$

Second, there is the no-information case: $(\varnothing, \varnothing)$. Firms cannot update beliefs about development costs, and maximize joint *ex ante* profits. The *ex ante* expected cost parameter is:

$$\theta_i^E(\varnothing, \varnothing) = p\underline{\theta} + (1 - p)\overline{\theta}, \text{ for } i = 1, 2.$$

Total expected development profit, given signals $\Theta = (\Theta_i, \Theta_j)$, is:

$$E_\theta \left\{ \sum_{\ell=1}^{2} \pi_\ell(D;\theta_\ell) \middle| \Theta \right\} = W \sum_{\ell=1}^{2} D_\ell - 2\Delta D_i D_j - \frac{1}{2} \sum_{\ell=1}^{2} \theta_\ell^E(\Theta) D_\ell^2.$$

This gives the following efficient development investment, $\overline{D}_i$ for firm i:

$$\theta_i^E(\Theta)\overline{D}_i = W - 2\Delta\overline{D}_j \Rightarrow \overline{D}_i(\Theta) = \frac{W}{\theta_i^E(\Theta) + 2\Delta}, \text{ with } i = 1, 2.$$

Note that firms' efficient development investments decrease in their expected development cost parameter $\theta_i^E(\Theta)$. The more pessimistic firms are about their costs of development the less they invest in developing the innovation. The efficient expected development profit is the following:

$$\overline{\pi}_i(\Theta) \equiv E_\theta \left(\pi_i(\overline{D};\theta) \,|\Theta \right) = \frac{1}{2} W \overline{D}_i(\Theta), \text{ for } i = 1, 2.$$

Efficient Research Investments

In the first stage of the race firms make research investment decisions. By doing so, they choose the probability of getting informed about their development costs. Efficient research investments are determined by the trade-off between the marginal cost of investment, ρ, and the expected gain of becoming informed. This gain is the difference between the expected efficient profit when firms are informed, and the expected profit when firms remain uninformed. We show this in the remainder of this subsection.

Total expected profit of choosing research investments $R = (R_i, R_j)$, given its efficient development investments $\overline{D} = (\overline{D}_i, \overline{D}_j)$, is:

$$\begin{aligned} \sum_{\ell=1}^{2} \Pi_\ell(R) &= [1 - (1 - R_i)(1 - R_j)] \sum_{\ell=1}^{2} \left\{ p\overline{\pi}_\ell(\underline{\theta}) + (1-p)\overline{\pi}_\ell(\overline{\theta}) \right\} + \\ &\quad + (1 - R_i)(1 - R_j) \sum_{\ell=1}^{2} \overline{\pi}_\ell(\varnothing) - \frac{1}{2}\rho \left(R_i^2 + R_j^2 \right). \end{aligned}$$

Maximizing total profits with respect to R_i gives first-order condition $\rho R_i = (1 - R_j)A$, where

$$\begin{aligned} A &\equiv \sum_{\ell=1}^{2} \left\{ p\overline{\pi}_\ell(\underline{\theta}) + (1-p)\overline{\pi}_\ell(\overline{\theta}) - \overline{\pi}_\ell(\varnothing) \right\} \\ &= p\frac{W^2}{\underline{\theta} + 2\Delta} + (1-p)\frac{W^2}{\overline{\theta} + 2\Delta} - \frac{W^2}{E(\theta) + 2\Delta}, \end{aligned}$$

and $A > 0$.[6] The marginal revenue of research investments is the total expected profit added to the industry from being informed instead of uninformed. The efficient research investments are:

$$\overline{R}_i = \frac{A}{\rho + A}, \text{ for } i = 1, 2.$$

In the following sections we study how noncooperative firms choose their investments, and how these investments relate to the efficient ones.

4.3.2 Mandated Disclosure Equilibrium (PPC)

In this section we study the equilibrium in which firms are required to disclose their information $\Theta = (\Theta_i, \Theta_j)$. Such a disclosure regulation could be implemented by the threat of severe penalties after withholding of information is discovered. Such a regulation is effectively chosen by the European Medical Evaluation Agency for evaluating medicine innovations. Observe that the only difference between the benchmark and this case is that we introduce competition in research and development. The first subsection characterizes the equilibrium development investments, $\widehat{D}$, given the research investments and full disclosure. Typically, firms overinvest in development, because of a "business-stealing effect". The second subsection characterizes the equilibrium investments, $\widehat{R}$. Firms underinvestment in research is due to a free-rider effect in information acquisition.

Full Disclosure Development Equilibrium

Equilibrium development investments are determined again by the trade-off between revenues and costs of development. However, firms do not internalize the adverse effect that an increase in their development investment causes on the chances of their rival to win the race. This causes them to overinvest in development, which is shown in the remainder of this subsection.

Firm i chooses development investment D_i to maximize expected profit, given signals Θ and resulting expected cost parameter $\theta_i^E(\Theta)$:

$$E_\theta[\pi_i(D; \theta)|\Theta] = D_i W - \Delta D_i D_j - \frac{1}{2}\theta_i^E(\Theta) D_i^2, \text{ for } i = 1, 2.$$

[6]Since the function $f(\theta) = \frac{1}{\theta + 2\Delta}$ is strictly convex for all $\theta > 0$, $pf(\underline{\theta}) + (1-p)f(\overline{\theta}) > f(p\underline{\theta} + (1-p)\overline{\theta})$. And therefore $A > 0$.

The first-order condition for profit maximization of firm i is the following.

$$\theta_i^E(\Theta)D_i = W - \Delta D_j.$$

This gives equilibrium investments:

$$\widehat{D}_i(\Theta) = \frac{W}{\theta_i^E(\Theta) + \Delta}.$$

Again equilibrium investments decrease in the expected costs of development. Note that these equilibrium investments are bigger than the optimal development investments $\overline{D}_i(\Theta)$. Firms that are required to disclose their information, overinvest in development. This is a standard observation in R&D races where investments are strategic substitutes. Expected equilibrium profits are:

$$\begin{aligned}\widehat{\pi}_i(\Theta) &\equiv E_\theta\left\{\pi_i\left(\widehat{D}(\Theta);\theta\right)\Big|\,\Theta\right\} = \widehat{D}_i(\Theta)\left(W - \widehat{D}_j(\Theta)\Delta\right) - \frac{1}{2}\theta_i^E(\Theta)\widehat{D}_i(\Theta)^2 \\ &= \frac{1}{2}\theta_i^E(\Theta)\widehat{D}_i(\Theta)^2 = \frac{\frac{1}{2}\theta_i^E(\Theta)W^2}{\left(\theta_i^E(\Theta)+\Delta\right)^2}.\end{aligned}$$

Full Disclosure Research Equilibrium

When firms choose research investments competitively, they prefer to free-ride on information acquired by their rival. A firm's research investments only contributes to its profit when its rival did not acquired information. In equilibrium firms therefore underinvest in research, which is shown in the remainder of this subsection.

Firm i chooses research investment R_i such that it maximizes its expected profit, given the equilibrium research investment of the rival firm, $\widehat{R}_j$, and anticipating equilibrium development investments, $\widehat{D}$. Firm i's expected revenue of learning its own cost of investment, $\Theta_i = \theta$, is:

$$p\widehat{\pi}_i(\underline{\theta}) + (1-p)\widehat{\pi}_i(\overline{\theta}).$$

The expected revenue from receiving $\Theta_i = \varnothing$ is:

$$R_j\left(p\widehat{\pi}_i(\underline{\theta}) + (1-p)\widehat{\pi}_i(\overline{\theta})\right) + (1-R_j)\widehat{\pi}_i(\varnothing).$$

The marginal revenue of obtaining an informative signal is therefore $(1-R_j)B$, where

$$\begin{aligned}B &\equiv p\widehat{\pi}_i(\underline{\theta}) + (1-p)\widehat{\pi}_i(\overline{\theta}) - \widehat{\pi}_i(\varnothing) \\ &= \frac{1}{2}W^2\left\{\frac{p\underline{\theta}}{(\underline{\theta}+\Delta)^2} + \frac{(1-p)\overline{\theta}}{(\overline{\theta}+\Delta)^2} - \frac{p\underline{\theta}+(1-p)\overline{\theta}}{(p\underline{\theta}+(1-p)\overline{\theta}+\Delta)^2}\right\}.\end{aligned}$$

Note that the firm's marginal revenue of information acquisition is only positively affected when the firm's rival failed to obtain any informative signal.[7] Whenever firm j managed to obtain an informative signal, firm i would prefer to incur no research cost and free-ride on firm j's information. Firm i's profit maximizing investments in research are such that marginal cost of research investment equals its marginal revenue: $\rho R_i = (1 - R_j)B$. Equilibrium research investments are the following:

$$\widehat{R}_i = \frac{B}{\rho + B}.$$

When we compare these equilibrium investments with the efficient research investments, we obtain the following. Under mandated disclosure each firm free-rides on the information acquired by its rival, while efficient research investments internalize this externality. This is stated in the following proposition.

Proposition 4.1 *Under PPC and mandated disclosure the following holds:*
(i) firms overinvest in development: $\widehat{D}_i(\Theta) > \overline{D}_i(\Theta)$, *for all* Θ, *and*
(ii) firms underinvest in information acquisition : $\widehat{R}_i \leq \overline{R}_i$ *for* $i = 1, 2$, *with strict inequality for interior research investment choices.*

This subsection characterized the equilibrium investments under mandated disclosure. We compared the equilibrium investments with the efficient investments. Free-rider incentives in information acquisition predominate when firms are required to disclose their information. In the next subsection we characterize firms' equilibrium investments and disclosure rules, when disclosure is voluntary.

4.3.3 Voluntary Disclosure (PPC)

In the preceding subsection firms were required to disclose their information. This section studies the equilibria in which firms disclose information voluntarily. Under PPC the informational effect is strongest for firms. Firms' incentives to conceal good news while disclosing bad news are strongest in this case. In this subsection we characterize equilibrium investments under this rule, and derive conditions under which concealment of good news and disclosure of bad news is indeed an equilibrium disclosure rule.

Solving the game backwards involves three stages. First we must solve for the equilibrium development investments, D^*, given firms partially disclose information,

[7] Since the function $g(\theta) = \frac{\theta}{(\theta+\Delta)^2}$ is strictly convex for all $\theta > 2\Delta$, $pg(\underline{\theta}) + (1-p)g(\overline{\theta}) > g(p\underline{\theta} + (1-p)\overline{\theta})$, and hence $B > 0$.

$\widetilde{\delta}$, expected disclosure rule $(\underline{\delta}_i, \overline{\delta}_i) = (\varnothing, \overline{\theta})$ and expected research investments, r. Second we solve for the equilibrium disclosure rules, δ^*, given the expected research investments and equilibrium development investments. And thirdly we determine the equilibrium research investments, R^*. This will be done in the following three subsections, respectively.

Voluntary Disclosure Development Equilibrium

In this subsection we characterize firms' development investments under partial disclosure. Both firms conceal good news, $\underline{\delta}_i = \varnothing$, while they disclose bad news about their project, $\overline{\delta}_i = \overline{\theta}$, with $i = 1, 2$. Obviously, firms' equilibrium development investments only differ from those under mandated disclosure when both firms send uninformative messages. Since firms with good news pool together with uninformed firms under partial disclosure, equilibrium development investment are affected in the following way. A firm with good news expects weaker competition from a concealing firm under partial disclosure than under mandated disclosure. It therefore invests more in development. An uninformed firm will be more optimistic about costs of development but expects stronger development competition under partial disclosure than under mandated disclosure. The informational effect dominates. Consequently it invests more in development. When expected research investments grow, we expect the following. A concealing firm is more likely to actually have good news. An informed firm therefore expects a stronger competitor, while an uninformed firm expects lower development costs. Therefore equilibrium development investments for the informed firm decrease, while those of the uninformed firm increase in expected research investments. We establish these results more extensively in the remainder of this subsection.

First determine the equilibrium beliefs. Obviously, when one firm disclosed high costs of investments, both firms expect $\theta = \overline{\theta}$, and invest $\widehat{D}(\overline{\theta})$ accordingly.

When firms' costs of development investments are perfectly correlated, there is only incomplete information between firms when neither firm disclosed any information, $(\widetilde{\delta}_i, \widetilde{\delta}_j) = (\varnothing, \varnothing)$. Firms are in one of the following two situations. When firm i receives signal $\Theta_i = \underline{\theta}$, it knows that its costs of development investments are low. A firm that receives an uninformative signal, $\Theta_i = \varnothing$, and faces a rival who does not disclose information, $\widetilde{\delta}_i = \varnothing$, knows that nobody received a high-cost signal. His rival was either uninformed or received a low-cost signal. Given this inference and given expected information acquisition investments, r_j, firm i updates its cost expectations by using Bayes' rule, which gives the following:

$$\begin{aligned}\Pr[\theta=\underline{\theta}|\widetilde{\delta}_j=\varnothing] &= \frac{\Pr[\Theta_j\neq\overline{\theta}|\theta=\underline{\theta}]\Pr[\theta=\underline{\theta}]}{\Pr[\Theta_j\neq\overline{\theta}|\theta=\underline{\theta}]\Pr[\theta=\underline{\theta}]+\Pr[\Theta_j\neq\overline{\theta}|\theta=\overline{\theta}]\Pr[\theta=\overline{\theta}]} \\ &= \frac{p}{p+(1-r_j)(1-p)}\equiv\alpha_j.\end{aligned}$$

This gives expected costs of development:

$$E_i^*(\theta|\varnothing)\equiv E_i(\theta|\Theta_i=\varnothing,\widetilde{\delta}_j=\varnothing)=\alpha_j\underline{\theta}+(1-\alpha_j)\overline{\theta}$$

Firm i's belief about firm j's private signal is then:

$$\Pr[\Theta_j=\underline{\theta}|\widetilde{\delta}_j=\varnothing]=\frac{\Pr[\Theta_j=\underline{\theta}]}{\Pr[\Theta_j=\underline{\theta}]+\Pr[\Theta_j=\varnothing]}=\frac{pr_j}{pr_j+1-r_j}=\alpha_j r_j.$$

Given these beliefs, development investments are the following. When no information was disclosed, firms update their beliefs, maximize expected profits given no disclosure, and consequently invest in line with the following first-order conditions:

$$\underline{\theta}D_i^*(\underline{\theta}) = W-\left(r_jD_j^*(\underline{\theta})+(1-r_j)D_j^*(\varnothing)\right)\Delta \tag{4.1}$$

$$E_i^*(\theta|\varnothing)D_i^*(\varnothing) = W-\left(\frac{pr_j}{pr_j+1-r_j}D_j^*(\underline{\theta})+\frac{1-r_j}{pr_j+1-r_j}D_j^*(\varnothing)\right)\Delta. \tag{4.2}$$

When we solve this system of linear equation, we obtain the four equilibrium development investments. About the equilibrium development investments of informed firms with low-cost signal, $D^*(\underline{\theta})$, we can say the following. The firm that is expected to have invested more (resp. less) in information acquisition, invests more (resp. less) in development, when it receives a low cost signal:[8]

$$D_i^*(\underline{\theta})>D_j^*(\underline{\theta})\Leftrightarrow r_i>r_j,\text{ for }i,j=1,2\text{ and }i\neq j.$$

When your rival invests relatively little in research, you assign relatively little probability to facing an informed, aggressive rival. This gives you a relatively bigger incentive to invest in development. Therefore equilibrium development investments are bigger than those of your rival.

For uninformed firms the reverse holds. The uninformed firm who is expected to have invested more (resp. less) in information acquisition, invests less (resp. more) in development:

$$D_i^*(\varnothing)>D_j^*(\varnothing)\Leftrightarrow r_i<r_j,\text{ for }i,j=1,2\text{ and }i\neq j.$$

[8]Note that $D_i^*(\underline{\theta})-D_j^*(\underline{\theta})$ is proportional to $(1-p)^2\Delta W(1-r_i)(1-r_j)(\overline{\theta}-\Delta)(\overline{\theta}-\underline{\theta})(r_i-r_j)$, which gives the observation directly.

When your rival expects that you invested relatively little in research, this has two effects. On the one hand your rival expects you to become relatively less pessimistic after receiving no informative signal and message. Given that you will be uninformed, this gives you a strategic advantage compared to your rival, and increases your incentives to invest in development. On the other hand your rival expects you to become uninformed relatively more often. This makes your rival expect a relatively weaker competitor. However, the former effect dominates the latter. Therefore an uninformed firm who is expected to invest relatively little in research invests more aggressively in development under partial disclosure.

With symmetric expected research investments, $r_i = r$ and $\alpha_i = \alpha$ for $i = 1, 2$, the equilibrium development investments under partial disclosure become:

$$\begin{aligned} D_i^*(\underline{\theta}) &= \frac{\left(\alpha\underline{\theta} + (1-\alpha)\overline{\theta} + r(1-\alpha)\Delta\right) W}{\left(\underline{\theta} + r\Delta\right)\left(\alpha\underline{\theta} + (1-\alpha)\overline{\theta}\right) + \left((1-r\alpha)\underline{\theta} + r(1-\alpha)\Delta\right)\Delta}, \\ D_i^*(\varnothing) &= \frac{\left(\underline{\theta} + r(1-\alpha)\Delta\right) W}{\left(\underline{\theta} + r\Delta\right)\left(\alpha\underline{\theta} + (1-\alpha)\overline{\theta}\right) + \left((1-r\alpha)\underline{\theta} + r(1-\alpha)\Delta\right)\Delta}, \end{aligned}$$

for $i = 1, 2$. Observe that $D_i^*(\underline{\theta}) \geq D_i^*(\varnothing)$. When we compare firm i's development investment first-order conditions we note the following. An uninformed firm has higher expected costs, but expects weaker competition. The direct effect of lower costs dominates the indirect competition effect. Therefore firms with low cost signals invest more than uninformed firms in symmetric development equilibrium.

Observe that for symmetric expected research investments equilibrium development investments depend in the following way on the expected research investments:

$$\begin{aligned} \frac{\partial D_i^*(\underline{\theta})}{\partial r} &= \frac{-(1-p)(1-r)\Delta(\overline{\theta}-\underline{\theta})\left((1-p)(1-r)(\overline{\theta}+\Delta) + 2p\underline{\theta}\right) W}{\left[\left(\underline{\theta} + r\Delta\right)\left(\alpha\underline{\theta} + (1-\alpha)\overline{\theta}\right) + \left((1-r\alpha)\underline{\theta} + r(1-\alpha)\Delta\right)\Delta\right]^2} \leq 0, \\ \frac{\partial D_i^*(\varnothing)}{\partial r} &= \frac{p(1-p)\underline{\theta}(\overline{\theta}-\underline{\theta})\left(\underline{\theta} - (1-2r)\Delta\right) W}{\left[\left(\underline{\theta} + r\Delta\right)\left(\alpha\underline{\theta} + (1-\alpha)\overline{\theta}\right) + \left((1-r\alpha)\underline{\theta} + r(1-\alpha)\Delta\right)\Delta\right]^2} \geq 0. \end{aligned}$$

Note that we change both r_i and r_j in equal amounts in the same direction. Typically when $r_i = r_j = 1$ equilibrium both development investment $D_i^*(\underline{\theta})$ and $D_i^*(\varnothing)$ coincides with the full information development investment $\widehat{D}_i(\underline{\theta})$. When firms are expected to be fully informed, the distinction between disclosure and concealment is no longer relevant. Rational firms anticipate their rival's disclosure strategy and update beliefs accordingly. That is, when it is expected that firms are informed with certainty, the "unraveling result" holds.[9] When both expected research investments

[9]Note that it is not the perfect correlation between firms' costs of development investments that

increase, it becomes more likely that firms are informed. This implies that firms expect to face stronger competition in development. This discourages investments of firms. Therefore equilibrium investments of low cost firms decrease in the expected research investments. An increase in expected research investments also makes an uninformed firms more optimistic about their own costs of development. Since your rival is less likely to be uninformed, an uninformative message from him becomes a better indication to you that he actually is concealing good news about development costs. This positive cost effect dominates the negative effect of expecting fiercer competition.

When we compare the symmetric development investments under partial disclosure with those under mandated disclosure, we observe the following. Given a firm's individual development cost signal, each firm invests more under partial disclosure than under full disclosure. That is, $D_i^*(\underline{\theta}) > \widehat{D}_i(\underline{\theta})$ and $D_i^*(\varnothing) > \widehat{D}_i(\varnothing)$, for $i = 1, 2$. When firm i knows that it has low development costs, it expects weaker competition under partial disclosure than under full disclosure, which encourages higher investments. Under voluntary disclosure an uninformed firm expects lower development costs, but expects stronger competition. The (direct) cost effect is the dominating effect. However, this does not mean that the overall overinvestment in development is increased. Because a low-cost firm conceals its costs, there are contingencies, $(\underline{\theta}, \varnothing)$ and $(\varnothing, \underline{\theta})$, under which one of the firms remains uninformed under partial disclosure. And this uninformed firm invests less in development than its informed counterpart: $D_i^*(\varnothing) < \widehat{D}_i(\underline{\theta})$.

We summarize our results on equilibrium development investments under partial disclosure in the following proposition.

Proposition 4.2 *For PPC, partial disclosure* $(\underline{\delta}_i, \overline{\delta}_i) = (\varnothing, \overline{\theta})$, $r_i < 1$, *and* $i = 1, 2$, $i \neq j$, *the following holds:*
(i) For $r_i < r_j$: $D_i^*(\underline{\theta}) < D_j^*(\underline{\theta})$ *and* $D_i^*(\varnothing) > D_j^*(\varnothing)$,
(ii) For $r_i = r_j = r$:
(ii.a) $D_i^*(\underline{\theta}) > D_i^*(\varnothing)$, *while* $\frac{\partial D_i^*(\underline{\theta})}{\partial r} < 0$ *and* $\frac{\partial D_i^*(\varnothing)}{\partial r} > 0$, *for* $r < 1$,
(ii.b) $\widehat{D}_i(\varnothing) \leq D_i^*(\varnothing) < \widehat{D}_i(\underline{\theta}) < D_i^*(\underline{\theta})$, *for* $r < 1$,
(ii.c) $D_i^*(\varnothing) = \widehat{D}_i(\varnothing)$ *for* $r = 0$, *while* $D_i^*(\underline{\theta}) = D_i^*(\varnothing) = \widehat{D}_i(\underline{\theta})$ *for* $r = 1$.

causes this result. The result is obtained through firms' inferences that are consistent with the anticipated disclosure rule. It is not necessary that firms are actually completely informed about the true costs of investments, and therefore have perfectly correlated costs. It only matters that in the firms' perception, no concealment is possible, since firms cannot credibly claim to be uninformed.

Equilibrium Disclosure Strategies

Since the informational effect is strongest under PPC, we would expect it to outweigh the strategic effect of information disclosure. This indeed happens in most cases, typically. In that case we expect that full disclosure cannot be an equilibrium, since firms prefer to deviate by concealing good news. Nor can full concealment be an equilibrium disclosure rule, because a high cost firm prefers to unilaterally disclose its information. Furthermore, we show that there is indeed a sufficient condition under which firms partially disclose their information irrespective of their expectations on research investments. This is done in the remainder of this subsection.

Given expected research investments (r_i, r_j), cost signals (Θ_i, Θ_j), and anticipated equilibrium development investments $(D_i(\Theta_i, \widetilde{\delta}), D_j(\Theta_j, \widetilde{\delta}))$, for all Θ and $\widetilde{\delta}$, we determine firms' equilibrium disclosure rules. We focus on pure strategy symmetric disclosure equilibria. First, we establish the following negative result.

Lemma 4.1 *For PPC and $r_i < 1$, with $i = 1, 2$, the following symmetric combinations of disclosure rules are not chosen in equilibrium:*
(i) Full disclosure of information, $(\underline{\delta}_i, \overline{\delta}_i) = (\underline{\theta}, \overline{\theta})$,
(ii) Partial disclosure with disclosure of low cost only, $(\underline{\delta}_i, \overline{\delta}_i) = (\underline{\theta}, \varnothing)$,
(iii) No disclosure of any information, $(\underline{\delta}_i, \overline{\delta}_i) = (\varnothing, \varnothing)$.

The proposed disclosure rules are not chosen in equilibrium, because firms have either an incentive to conceal a low cost signal, as in (i), an incentive to disclose a high cost signal, as in (iii), or both, as in (ii). In general firms have an incentive to manipulate the disclosed information such that it makes their rival more pessimistic about their costs of development investment. This is due to the informational effect. The indirect, strategic effect of such a disclosure rule is that it makes the rival more optimistic about the concealing firm's development investments. The strategic effect is however offset by the informative effect in this setting. This suggests that disclosing only high costs of investment could be an equilibrium disclosure rule. In the next proposition we argue that disclosing only high costs is indeed an equilibrium rule under a certain condition.

Proposition 4.3 *If*

$$p \geq \frac{(\overline{\theta} - \Delta)\Delta}{(\overline{\theta} - \Delta)\Delta + (\underline{\theta} - \Delta)\underline{\theta}}, \tag{4.3}$$

then partial disclosure $(\underline{\delta}_i^*, \overline{\delta}_i^*) = (\varnothing, \overline{\theta})$ *is an equilibrium disclosure rule for any expected research investments* (r_i, r_j) *under PPC.*

From this proposition we can conclude that under condition (4.3) the informational effect dominates the strategic effect of information disclosure under PPC. By disclosing bad news, and concealing good news, firms make their rival pessimistic about the actual costs of development investment.

In the next subsection we assume that condition (4.3) is met. We can therefore focus attention on equilibrium candidates in which symmetric partial disclosure occurs. In the next subsection we characterize the equilibrium research investments when partial equilibrium disclosure and its resulting equilibrium development investments are anticipated. We conclude the analysis of the PPC race by discussing what happens when sufficient condition (4.3) is violated, and making concluding remarks.

Voluntary Disclosure Research Equilibrium

In this subsection we derive and characterize the equilibrium research investments, given equilibrium disclosure rules $\delta_i^* = (\underline{\delta}_i^*, \overline{\delta}_i^*) = (\varnothing, \overline{\theta})$, with $i = 1, 2$, and development investments D^*. In which direction incentives for research change when we move from mandated to partial disclosure, is not immediately clear. When research investments result in an informative signal for a firm, this enables it to be a more aggressive development competitor and gain higher expected profits. This clearly increases firms' incentives to acquire information under voluntary disclosure. However, an uninformative signal gives rise to a trade-off. On the one hand, when both firms are uninformed, they are less pessimistic and reach a higher expected profit under voluntary disclosure. This gives an uninformed firm a lower incentive to invest under voluntary disclosure. On the other hand, when the uninformed firm's rival actually received bad news, the uninformed firm can no longer take a free-ride on this information, which gives it a bigger incentive to acquire information under voluntary disclosure. The increased incentive of being informed and foregoing information free-riding outweighs the disincentive of lower pessimism. We confirm this in the remainder of this subsection.

In the previous subsection we observed that under condition (4.3) of the proposition firms always partially disclose information. In that case firm i's anticipated expected profits, given research investments, $R = (R_i, R_j)$, equilibrium disclosure rules, development investments and beliefs, are the following:

$$\begin{aligned} E_\theta\left\{\pi_i(D^*;\theta)|R\right\} &= pR_i\pi_i\left(D_i^*(\underline{\theta}), D_j^*;\underline{\theta}\right) + p(1-R_i)\pi_i\left(D_i^*(\varnothing), D_j^*;\underline{\theta}\right) + \\ &\quad +(1-p)\left(R_i + (1-R_i)R_j\right)\pi_i\left(D_i^*(\overline{\theta}), D_j^*;\overline{\theta}\right) + \\ &\quad +(1-p)(1-R_i)(1-R_j)\pi_i\left(D_i^*(\varnothing), D_j^*;\overline{\theta}\right) - \frac{\rho}{2}R_i^2. \end{aligned}$$

When we take the first-order condition towards R_i, and let firms' expectations be realized, $r_i = R_i$, we get equilibrium condition:

$$\begin{aligned} \rho R_i &= pR_j\left\{\pi_i^*(\underline{\theta}) - \pi_i^*(\varnothing)\right\} + (1-R_j)\left\{p\pi_i^*(\underline{\theta}) + (1-p)\pi_i^*(\overline{\theta}) - \pi_i^*(\varnothing)\right\} \\ &= p\frac{1}{2}\underline{\theta}D_i^*(\underline{\theta})^2 - \frac{1}{2}\left(p\underline{\theta} + (1-p)(1-R_j)\overline{\theta}\right)D_i^*(\varnothing)^2 + \\ &\quad +(1-p)(1-R_j)\frac{1}{2}\overline{\theta}D_i^*(\overline{\theta})^2. \end{aligned}$$

With probability p the project has low costs of development. In that case a firm's rival never discloses information. Therefore a marginal increase in research investment could change a firm's revenue from that of an uninformed to that of a low-cost firm's revenue. When the project has high costs of investment, a firm's research investments only makes a difference if its rival did not obtain an informative signal on the costs. Because if the rival would get a high-cost signal, he would disclose it in equilibrium.

When we compare the research investments under required and voluntary disclosure, we observe the following.

Proposition 4.4 *For PPC, under condition (4.3) firms' symmetric equilibrium research investments under voluntary information disclosure exceed those under mandated information disclosure:* $R_i^* \geq \widehat{R}_i$ *for* $i = 1, 2$. *Strict inequality holds for interior equilibrium research investments.*

The intuition for this result is as follows. Since high development costs are always disclosed in equilibrium, the incentives to acquire information on high costs are the same under mandated and voluntary disclosure. We can therefore ignore high cost signals in comparing research incentives under voluntary and mandated disclosure. The incentives to learn low development costs differ between mandated and voluntary disclosure. When firm i's research investment results in a low cost signal, $\Theta_i = \underline{\theta}$, this generates more expected profit for a concealing firm than for a firm who is required to disclose this signal. This gives bigger research incentives under voluntary disclosure. When firm i's research investment did not result in a low cost signal, then either firm j received good news, $\Theta_j = \underline{\theta}$, or no firm received any information. When firm j received good news, firm i can take a free-ride on this acquired information under mandated disclosure. This gives firms under mandated disclosure a disincentive to invest in research. Given that no information is disclosed, firms become less pessimistic about their development costs, and generate a bigger expected return under voluntary disclosure than under mandated disclosure. This gives firms a disincentive to invest in research under voluntary disclosure. The disincentive from free-riding under mandated disclosure outweighs the disincentive from lower pessimism under voluntary disclosure. Therefore the total research incentive is bigger under voluntary disclosure then under mandated disclosure.

Conditions for Partial Equilibrium Disclosure

After the characterization of equilibrium investments in the regular case of partial disclosure, we discuss in more detail the conditions under which partial disclosure is indeed an equilibrium disclosure rule. Condition (4.3) is a sufficient condition for obtaining partial disclosure given any feasible combination of expected research investments. Necessary and sufficient conditions under which firms partially disclose information in equilibrium are stated in the following proposition.

Proposition 4.5 *Under PPC partial disclosure with firms disclosing only high cost information,* $(\underline{\delta}^*, \overline{\delta}^*) = (\varnothing, \overline{\theta})$*, is chosen in equilibrium iff*

$$r_j \leq \min\left\{1, \frac{\underline{\theta}\left(p\underline{\theta} + (1-p)\overline{\theta} - \Delta\right)}{(1-p)(\overline{\theta} - \Delta)\left(\underline{\theta} + (1-r_i)\Delta\right)}\right\} \tag{4.4}$$

and

$$r_j \geq \max\left\{0, \frac{(\underline{\theta} - \Delta)\left(p\underline{\theta} - (1-p)\Delta\right) + (1-p)(1-r_i)\left(\underline{\theta}\overline{\theta} - \Delta^2\right)}{(1-p)\left((1-r_i)(\overline{\theta} - \underline{\theta}) - r_i(\underline{\theta} - \Delta)\right)\Delta}\right\} \tag{4.5}$$

for $i, j = 1, 2$ $(i \neq j)$.

In figure 4.2 we illustrate the conditions of the proposition for parameter values $p = \frac{1}{50}$, $\Delta = \frac{1}{2}$, $W = 1$, $\underline{\theta} = 2$, $\overline{\theta} = 3$. Along the horizontal axis we put firm i's expected research investment, r_i, while along the vertical axis we put r_j. The solid boundaries represent the boundaries of condition (4.4), while the dashed boundaries represent boundaries of condition (4.5). For this numerical example condition (4.4) is stronger than condition (4.5). For other parameter values the reverse can hold.

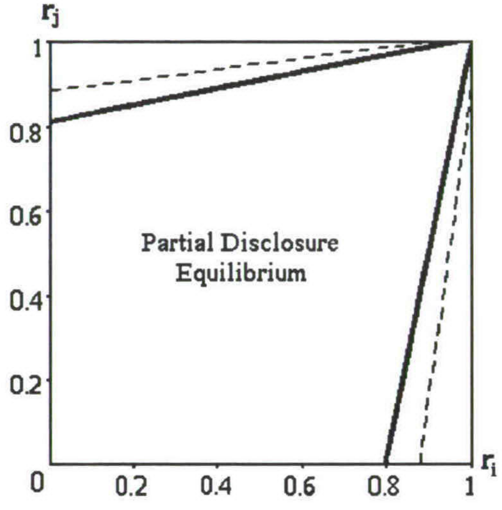

Figure 4.2: Partial disclosure region

Observe the tight link between expected information acquisition investments and equilibrium disclosure rules in this example. Not only do the information acquisition investments depend on the anticipated equilibrium disclosure rules, but also the equilibrium disclosure rules depend in a nontrivial way on the expected information acquisition investments.

From the proposition we can conclude that under conditions (4.4) and (4.5) the informational effect dominates the strategic effect of information disclosure under PPC. When one of the conditions is violated, the strategic effect is the dominating effect for one of the firms. When condition (4.4) is not met, unilateral disclosure of good news becomes profitable given beliefs that are consistent with partial disclosure. Parameter values for which this occurs are north-west and south-east of the solid lines in figure 4.2. Unilateral concealment of bad news becomes profitable when condition (4.5) is not met, given beliefs consistent with partial disclosure. The set of parameter values for which this is profitable are north-west and south-east of the dashed lines in figure 4.2. A firm has an incentive to unilaterally disclose (resp. conceal) to make its rival realize (resp. believe) that he is facing a "strong" competitor in the development stage of the race. In these situations firms' expected information acquisition investments and beliefs are such that the informational effect plays a minor role, and the strategic effect dominates. In the remainder of this subsection we discuss the intuition behind firms' incentives to deviate from partial disclosure in more detail. We discuss two cases. In the first case there is a firm who has an incentive to disclose good news. And in the second case there is a firm that has an incentive to conceal bad news.

■ First we consider the case in which firm i prefers to deviate from disclosure rule δ_i^* by *disclosing a low cost signal.* Take $\theta = \underline{\theta}$, and $r_i = \varepsilon$, $r_j = 1-\varepsilon$, with $\varepsilon, p > 0$ small. Suppose that firm j has equilibrium beliefs and investments, and firm i received an informative signal, $\Theta_i = \underline{\theta}$. When p is close to zero, an uninformed firm expects to have approximately high development costs $\overline{\theta}$, and does not expect to compete against a low-cost rival. An uninformed firm will therefore approximately invest $\widehat{D}_i(\overline{\theta})$, and be a weak competitor in the development stage.

If firm j receives a low-cost signal, it assigns probability ε to facing a low-cost rival, and probability $1-\varepsilon$ to facing a weak, uninformed firm. Since firm j puts high probability $(1-\varepsilon)$ on facing an uninformed rival, it becomes an aggressive investor in the development stage. Informed firm i, however, assigns high probability $(1-\varepsilon)$ to facing such a low-cost, aggressive rival, and probability ε to facing a weak, uninformed rival. This gives firm i a disincentive to invest in development. For low enough ε firm i's incentives to invest in development under information concealment are lower than those under information disclosure. Therefore firm i's expected profits under concealment are lower than its profit under disclosure. Firm i surprises its rival with the news that it will be an aggressive investor in the development stage by disclosing its low-cost signal. That is, informed firm j revises its beliefs about firm i's development investments drastically, which lowers its incentives to invest substantially. For small enough p and ε this strategic effect outweighs the informational effect of disclosure. We illustrate this in figure 4.3, with $p = \frac{1}{50}$, $r_i = \frac{1}{10}$, $r_j = \frac{9}{10}$, $\Delta = \frac{1}{2}$, $W = 1$, $\underline{\theta} = 2$, $\overline{\theta} = 3$. For these parameter values firm i's equilibrium investments under disclosure and concealment are $\widehat{D}_i(\underline{\theta}) = \frac{2}{5} \approx 0.400$ and $D_i^*(\underline{\theta}) = \frac{2{,}011{,}186}{5{,}034{,}931} \approx 0.399$ respectively. Along the horizontal (resp. vertical) axis we put firm i's (resp. firm j's) development investments. The solid lines represent the reaction functions of firms under disclosure, and the dashed lines represent the informed firms' "reduced-form" reaction curves under concealment.[10] Thin lines are used for firm i, and fat lines for firm j.

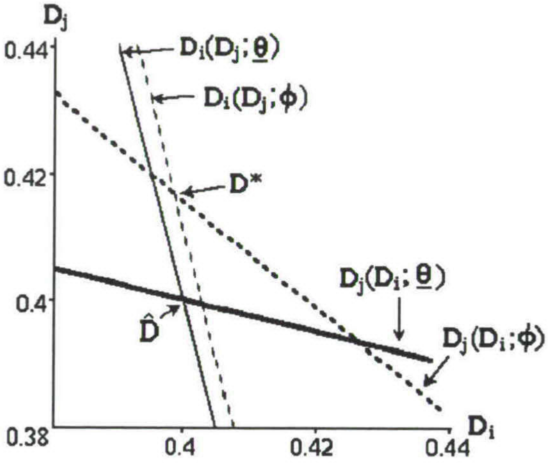

Figure 4.3: Reaction to disclosure of $\Theta_i = \underline{\theta}$.

Firm i's "reduced-form" reaction curve is only slightly shifted inwards after firm i discloses its information. Firm j's "reduced-form" reaction curve is much more affected after disclosure. This is due to the fact that this firm puts far less weight on competing against an informed rival before disclosure takes place. Figures 4.4.a, 4.4.b and 4.4.c sketch the development investments of concealing low-cost firms for parameter values $p = \frac{1}{50}$, $\Delta = \frac{1}{2}$, $W = 1$, $\underline{\theta} = 2$, $\overline{\theta} = 3$, and $r_i = \frac{1}{10}$, $\frac{1}{2}$ and $\frac{9}{10}$, respectively. On the horizontal axis we put firm j's expected research investment r_j, while on the vertical axis we put development investments $D_j^*(\underline{\theta})$ (dotted line), and $D_i^*(\underline{\theta})$ (solid line). The horizontal dashed line represents the level of development investments for a disclosing low-cost firm, $\widehat{D}_i(\underline{\theta})$.

[10]The "reduced-form" reaction curves of low-cost firms represent the relationship between low-cost firms' development investments after we solve the system of first-order conditions up to the development investments of low-cost firms.

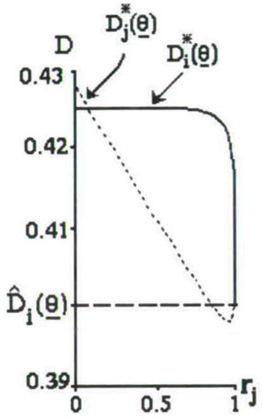

Figure 4.4.a: $r_i = \frac{1}{10}$

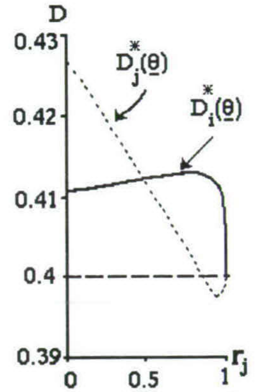

Figure 4.4.b: $r_i = \frac{1}{2}$

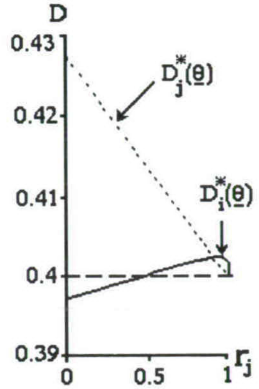

Figure 4.4.c: $r_i = \frac{9}{10}$

It is immediate from these figures that for $(r_i, r_j) = (\frac{1}{10}, \frac{9}{10})$ and $(r_i, r_j) = (\frac{9}{10}, \frac{1}{10})$, firm i's, respectively firm j's, low-cost concealment development investments $D_i^*(\underline{\theta})$, respectively $D_j^*(\underline{\theta})$, drop below the disclosure investments $\widehat{D}(\underline{\theta})$. This gives firm i, respectively firm j, an incentive to unilaterally disclose low costs for these expected research investments.

■ In the second case there is a firm who has an incentive to *conceal bad news*. Take $\theta = \overline{\theta}$, and $r_i = \varepsilon$, $r_j = 1 - \varepsilon$, with $\varepsilon, p > 0$ small. Suppose that firm j is uninformed and has equilibrium beliefs and investments, and firm i received a bad signal, $\Theta_i = \overline{\theta}$, and conceals. When ε is close to zero and no information is disclosed, firm j thinks that firm i is almost surely uninformed. If firm i would be uninformed, it would infer development costs $\underline{\theta}$ from firm j's uninformative message. Therefore firm j anticipates approximately equilibrium investment $\widehat{D}_i(\underline{\theta})$ from firm i. That is, firm j expects an aggressive rival after receiving an uninformative message, $\widetilde{\delta}_i = \varnothing$, from him. For ε close to zero firm j expects that firm i is uninformed too, which gives it expected cost of development equal to $p\underline{\theta} + (1-p)\overline{\theta}$. For low enough prior probability p firm j's expected development cost is approximately $\overline{\theta}$. That is, for sufficiently low p and ε firm j expects high development costs and an aggressive rival, which depresses its investments. These investments become in fact lower than $\widehat{D}_j(\overline{\theta})$. Therefore, firm i has an incentive to unilaterally conceal a high-cost signal. Concealment makes uninformed firm j expect aggressive development competition, which lowers its investments. This strategic effect of concealment dominates its informational effect. We illustrate this in figure 4.5 with $p = \frac{1}{50}$, $r_i = \frac{1}{10}$, $r_j = \frac{9}{10}$, $\Delta = \frac{1}{2}$, $W = 1$, $\underline{\theta} = 2$, $\overline{\theta} = 3$. For these parameter values firm i's equilibrium investments under disclosure and concealment are $\widehat{D}_j(\overline{\theta}) = \frac{2}{7} \approx 0.286$ and $D_j^*(\varnothing) = \frac{26,323,786}{92,186,851} \approx 0.285$, respectively. Along the horizontal (resp. vertical) axis we put firm i's (resp. firm j's) development investments. The solid lines represent the reaction functions of firms under disclosure, and the dashed lines represent the uninformed firms' "reduced-form" reaction curves under concealment. Thin lines are used for firm i, and fat lines for firm j.

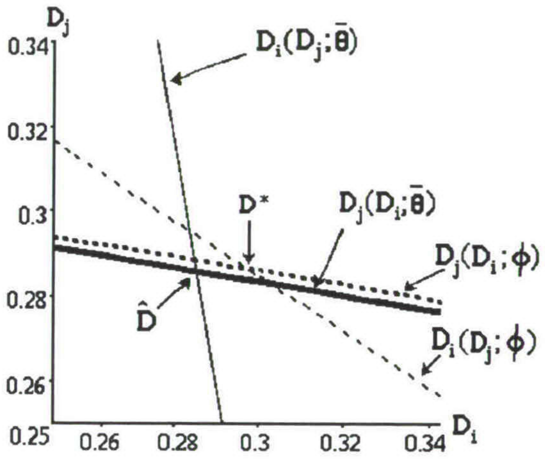

Figure 4.5: Reaction to concealment of $\Theta_i = \overline{\theta}$.

Now firm j's "reduced-form" reaction curve is only slightly shifted outwards after firm i conceals its information. Firm i's anticipated "reduced-form" reaction curve is much more affected after disclosure. This is due to the fact that an uninformed firm i puts high weight on having low costs of development, and competing against an informed rival. In fact firm i has high cost of development, and by concealing it makes its uninformed rival invest $D_j^*(\varnothing)$, which is less than $\widehat{D}_j(\overline{\theta})$. Figures 4.6.a, 4.6.b and 4.6.c sketch the development investments of uninformed firms for parameter values $p = \frac{1}{50}$, $\Delta = \frac{1}{2}$, $W = 1$, $\underline{\theta} = 2$, $\overline{\theta} = 3$, and $r_i = \frac{1}{10}$, $\frac{1}{2}$ and $\frac{9}{10}$, respectively. On the horizontal axis we put firm j's expected research investment r_j, while on the vertical axis we put development investments $D_j^*(\varnothing)$ (dotted line), and $D_i^*(\varnothing)$ (solid line). The dashed line represents the high-cost firms development investments after disclosure, $\widehat{D}_i(\overline{\theta})$.

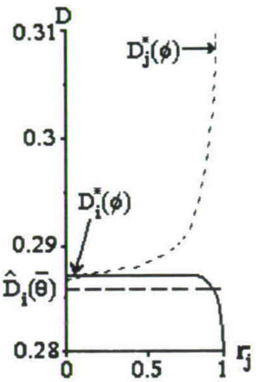

Figure 4.6.a: $r_i = \frac{1}{10}$

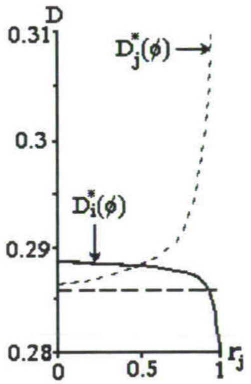

Figure 4.6.b: $r_i = \frac{1}{2}$

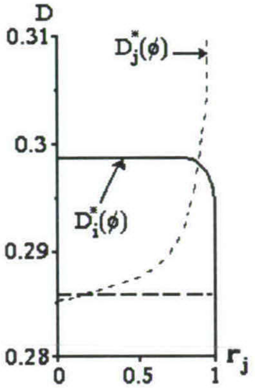

Figure 4.6.c: $r_i = \frac{9}{10}$

It is clear from these figures that for $r_i = \frac{1}{10}$ and $r_j = \frac{9}{10}$ uninformed firm j's investment $D_j^*(\varnothing)$ drops below $\widehat{D}_j(\overline{\theta})$, while for $r_i = \frac{9}{10}$ and $r_j = \frac{1}{10}$ firm i's $D_i^*(\varnothing)$ drops below $\widehat{D}_i(\overline{\theta})$. Therefore firm i, respectively firm j, has an incentive to unilaterally conceal its high costs in these cases.

The preceding examples of profitable unilateral deviations rely heavily on asymmetry between firms' expected research investments. It is immediate that conditions (4.4) and (4.5) are always met for symmetric expected information acquisition investments: $r_i = r_j$.[11] We also saw that the examples worked in particular for small prior probability p. For big enough prior probability p, i.e. p as in condition (4.3), we always get partial disclosure in equilibrium. When expected research investments are asymmetric and the prior probability is sufficiently small, we would expect asymmetric, and possibly mixed equilibrium disclosure rules. The characterization of the equilibrium disclosure rules for these asymmetric cases await future research.

Conclusion (PPC)

In this section we have seen that incentives to invest in research and development are greatly affected by disclosure regulation. When disclosure is mandated, firms underinvest in research, while they overinvest in development in every continuation game of the race. When disclosure is voluntary, the following observations were made in general. Both firms conceal good news and disclose bad news to their rival for high enough prior p. This makes their rival pessimistic about its costs of development,

[11] This follows directly from studying the conditions (see, e.g. figure 4.2), and from the characterization of symmetric equilibrium development investments under partial disclosure in the previous subsection. In particular, recall that for $r_i = r_j$, $D_i^*(\underline{\theta}) \geq \widehat{D}_i(\underline{\theta})$ and $D_i^*(\varnothing) \geq \widehat{D}_i(\overline{\theta})$, for $i = 1, 2$.

and discourages development investments. Such a disclosure rule makes firms more aggressive than under mandated disclosure in the development stage of the race. Informed investors are more aggressive because they expect more pessimistic and therefore weaker competitors in the development stage. Uninformed investors invest more in development, because they are more optimistic about their own costs of investment. It should however be noted that under voluntary disclosure there are relatively weaker, uninformed firms in the development stage given expected research intensities. Strategically disclosing firms invest more in research than fully disclosing firms.

In the next section we study how these results depend on the assumption on the correlation of development costs.

4.4 Identical Independent Distribution (IID)

In this section we study the situation in which firms are working on projects that have independently distributed costs of development. Prior probabilities are as follows: $\Pr[\theta_i = \underline{\theta}] = p$ and $\Pr[\theta_i = \overline{\theta}] = 1 - p$, for $i = 1, 2$, with θ_1 and θ_2 independent. With independently distributed costs firms can no longer free ride on their rival's information acquisition investments. A firm can only rely on its own acquired information to know its costs of investment. It should be clear that this implies that the informational effect of information disclosure no longer plays a role under IID. Since the informational effect was the dominating effect under PPC, it is not surprising that equilibrium investments and disclosure rules differ greatly compared to those in the previous subsection. We show in what direction the race's equilibrium changes in the remainder of this section.

IID differs in at least two respects from PPC. First, under IID costs of development can differ among firms. Therefore investments do not only depend on the absolute magnitude of a firm's costs, but also on how these costs relate to the rival's cost of development. The more efficient a firm is compared to its rival, the bigger its equilibrium development investments. A second difference with PPC is that under IID firms no longer learn about their own costs from observing their rival's cost signal. Firms' expected costs of development only depend on their own cost signal, and there is no more scope for the informational effect. This means that firms still have an incentive to acquire information when they expect that their rival will be informed.

In the first subsection we study the benchmark investments. Second we compare equilibrium investments under mandated disclosure with the benchmark investments. In subsection 3 we characterize equilibrium investments and disclosure rules under voluntary disclosure, and compare them with investments under mandated disclosure. Finally we conclude with some summarizing remarks. All proofs are relegated to the Appendix.

4.4.1 Benchmark: Efficient Investments (IID)

Efficient development investments depend on both the absolute and relative magnitude of firms' costs. Under IID firm i's expected cost of development parameter only depends on its own cost signal (for $i = 1, 2$):

$$\theta_i^E(\Theta_i) = \begin{cases} \underline{\theta}, \text{ for } \Theta_i = \underline{\theta} \\ p\underline{\theta} + (1-p)\overline{\theta}, \text{ for } \Theta_i = \varnothing \\ \overline{\theta}, \text{ for } \Theta_i = \overline{\theta}. \end{cases}$$

■ Again it is best for joint profits to disclose all information Θ. Total expected development profit, given signals Θ, is:

$$\begin{aligned} &E_\theta \left\{ \pi_i(D;\theta_i) + \pi_j(D;\theta_j) \,|\Theta \right\} = \\ &(D_i + D_j)W - 2\Delta D_i D_j - \frac{1}{2}\left(\theta_i^E(\Theta_i)D_i^2 + \theta_j^E(\Theta_j)D_j^2\right). \end{aligned}$$

This gives the following efficient development investments for firm i:

$$\begin{aligned} &\theta_i^E(\Theta_i)\overline{D}_i = W - 2\Delta\overline{D}_j \\ \Rightarrow \quad &\overline{D}_i(\Theta) = \frac{W\left(\theta_j^E(\Theta_j) - 2\Delta\right)}{\theta_i^E(\Theta_i)\theta_j^E(\Theta_j) - 4\Delta^2}, \text{ with } i, j = 1, 2,\ i \neq j. \end{aligned}$$

Note that it is efficient when firm i is expected to be more efficient, $\theta_i^E(\Theta_i) < \theta_j^E(\Theta_j)$, to let it invest relatively more in development. For given rival's expected development costs $\theta_j^E(\Theta_j)$, firm i's efficient development investments decrease in its expected costs, $\theta_i^E(\Theta_i)$. And a firm's efficient development investments increase in its rival's expected cost of development, given its own expected costs. The efficient expected development profit is the following:

$$\overline{\pi}_i(\Theta) \equiv E_\theta\left(\pi_i(\overline{D};\theta_i)\,|\Theta\right) = \frac{1}{2}W\overline{D}_i(\Theta), \text{ for } i = 1, 2.$$

■ The efficient research investments are determined by maximizing total expected profits, given efficient development investments. Firm i's expected profit, given efficient development investments is:

$$\begin{aligned}\overline{\Pi}_i(R) &= R_i\left\{R_j E_{\theta_j}\left(E_{\theta_i}[\overline{\pi}_i(\theta_i,\theta_j)]\right)+(1-R_j)E_{\theta_i}[\overline{\pi}_i(\theta_i,\varnothing)]\right\}+\\ &\quad +(1-R_i)\left\{R_j E_{\theta_j}(\overline{\pi}_i(\varnothing,\theta_j))+(1-R_j)\overline{\pi}_i(\varnothing,\varnothing)\right\}-\frac{\rho}{2}R_i^2,\end{aligned}$$

with

$$\begin{aligned}E_{\theta_i}[\overline{\pi}_i(\theta_i,\Theta_j)] &= p\overline{\pi}_i(\underline{\theta},\Theta_j)+(1-p)\overline{\pi}_i(\overline{\theta},\Theta_j) \text{ and}\\ E_{\theta_j}\left(h_i(\Theta_i,\theta_j)\right) &= ph_i(\Theta_i,\underline{\theta})+(1-p)h_i(\Theta_i,\overline{\theta}),\end{aligned}$$

for $i,j=1,2$ and $i\neq j$. When we maximize total expected profits, $\sum_{\ell=1}^{2}\overline{\Pi}_\ell(R)$, towards research investment R_i we obtain first-order condition:

$$\begin{aligned}\rho R_i &= R_j E_{\theta_j}\left\{E_{\theta_i}\left(\sum_{\ell=1}^{2}\overline{\pi}_\ell(\theta_i,\theta_j)\right)-\sum_{\ell=1}^{2}\overline{\pi}_\ell(\varnothing,\theta_j)\right\}+\\ &\quad +(1-R_j)\left\{E_{\theta_i}\left(\sum_{\ell=1}^{2}\overline{\pi}_\ell(\theta_i,\varnothing)\right)-\sum_{\ell=1}^{2}\overline{\pi}_\ell(\varnothing,\varnothing)\right\}.\end{aligned}$$

It is easy to verify that $\sum_{\ell=1}^{2}\overline{\pi}_\ell(\Theta)$ is convex in $\theta_i^E(\Theta_i)$ for any $\theta_j^E(\Theta_j)$. Hence, efficient research investments are non-negative, $\overline{R}_i>0$. Note that cost of research parameter, ρ, must be "big enough" to obtain an interior research solution, $\overline{R}_i<1$.[12] We will assume that this holds.

4.4.2 Mandated Disclosure Equilibrium (IID)

Under mandated disclosure firms still do not internalize the negative effect of an increase in their development investment on the expected revenue of their rival. We therefore expect that firms generically overinvest in development. Concerning research we know that free-rider effects no longer play a role for firms' incentives. Firms therefore no longer need to underinvest in research. We show that this actually happens in equilibrium in many cases.

■ When firms are required to disclose their signals, they base their development investment decision on their relative costs of development investment. Firm i's expected profits given firms' signals (Θ_i,Θ_j) are:

$$E_\theta\left(\pi_i(D;\theta_i)\,|\Theta\right)=D_iW-\Delta D_iD_j-\frac{1}{2}\theta_i^E(\Theta_i)D_i^2.$$

[12]Due to symmetry, it suffices to assume that:

$$\rho>E_{\theta_j}\left\{E_{\theta_i}\left(\sum_{\ell=1}^{2}\overline{\pi}_\ell(\theta_i,\theta_j)\right)-\sum_{\ell=1}^{2}\overline{\pi}_\ell(\varnothing,\theta_j)\right\}.$$

Profit maximization gives equilibrium development investment and profit:

$$\begin{aligned}\widehat{D}_i(\Theta) &= \frac{W\left(\theta_j^E(\Theta_j)-\Delta\right)}{\theta_i^E(\Theta_i)\theta_j^E(\Theta_j)-\Delta^2} \text{ and} \\ \widehat{\pi}_i(\Theta) &\equiv E_\theta\left(\pi_i(\widehat{D};\theta_i)\,|\Theta\right)=\frac{1}{2}\theta_i^E(\Theta_i)\widehat{D}_i(\Theta)^2,\end{aligned}$$

respectively, with $i,j=1,2,\ i\neq j$. Firm i's equilibrium development investments depend on expected development costs $\theta_i^E(\Theta_i)$ and $\theta_j^E(\Theta_j)$ in a similar fashion as its efficient investments do. The following is easily verified for $i=1,2$ and $i\neq j$.

Lemma 4.2 *For IID the following holds. When firms are expected to be equally efficient, $\theta_i^E(\Theta_i)=\theta_j^E(\Theta_j)$, both firms overinvest in development. When firm i is more efficient than firm j, $\theta_i^E(\Theta_i)<\theta_j^E(\Theta_j)$, then inefficient firm j always overinvests, while efficient firm i overinvests iff $\theta_i^E(\Theta_i)>\frac{(3\theta_j^E(\Theta_j)-2\Delta)\Delta}{\theta_j^E(\Theta_j)}$.*

A direct consequence of this lemma is that firms always overinvest in development if $\underline{\theta}\geq 3\Delta$.[13]

■ In the research stage each firm maximizes expected profits, given anticipated equilibrium development investments, $\widehat{D}$. Firm i's expected profit, given equilibrium development investments, $\widehat{\Pi}_i(R)$, is as $\overline{\Pi}_i(R)$ with $\overline{\pi}_i(\Theta)$ replaced by $\widehat{\pi}_i(\Theta)$. Maximizing $\widehat{\Pi}_i(R)$ towards R_i gives first-order condition:

$$\begin{aligned}\rho R_i &= R_j E_{\theta_j}\left\{E_{\theta_i}\left(\widehat{\pi}_i(\theta_i,\theta_j)\right)-\widehat{\pi}_i(\varnothing,\theta_j)\right\}+ \\ &\quad +(1-R_j)\left\{E_{\theta_i}\left(\widehat{\pi}_i(\theta_i,\varnothing)\right)-\widehat{\pi}_i(\varnothing,\varnothing)\right\},\end{aligned}$$

for $i,j=1,2,\ i\neq j$. Since $\widehat{\pi}_i(\Theta)$ is convex in $\theta_i^E(\Theta)$, it is immediate that $\widehat{R}_i>0$, for $i=1,2$. In order to obtain an interior solution of this system of equations for R_i, we have to put a lower-bound on ρ.

Suppose that we get symmetric, interior optimal and equilibrium research investments under mandated disclosure. Then we can illustrate that firms can either under- or overinvest in equilibrium, depending on the parameter values.

Proposition 4.6 *For IID the following holds:*
(i) If $\underline{\theta}\geq 3\Delta$, then firms overinvest in research, $\widehat{R}_i\geq\overline{R}_i$.
(ii) If $\Delta=\frac{1}{2}$, $\underline{\theta}=\frac{101}{100}$, $\overline{\theta}=\frac{102}{100}$, then firms underinvest in research, $\widehat{R}_i\leq\overline{R}_i$.
These inequalities are strict for interior equilibrium research investments.

[13] Note that function $\ell(\theta):=\frac{(3\theta-2\Delta)\Delta}{\theta}$ increases in θ, with $\lim\limits_{\theta\to\infty}\ell(\theta)=3\Delta$, hence $\ell(\theta)<3\Delta$.

Part (i) of the proposition gives a result that is opposite to that under PPC. For $\underline{\theta} \geq 3\Delta$ firms always underinvest in research under PPC, while they overinvest under IID. Because firms can no longer free-ride on research investments of their rival, their incentives to acquire information increases.

4.4.3 Voluntary Disclosure (IID)

In this subsection we show that firms strategically preannounce innovations. A firm who discloses good news and conceals bad news about its project discourages its rival in further developing the innovation. Disclosure of only low development costs leaves the rival's expected development cost unaffected, while it makes it expect strong competition in the development stage. We call such a disclosure choice "vaporware". We characterize development investments under vaporware, establish that vaporware is indeed an equilibrium disclosure rule, and discuss equilibrium research investments under vaporware in the following three subsections, respectively.

Equilibrium Development Investments

In this subsection we derive the equilibrium development investment, given expected research investments, (r_i, r_j), disclosure rules, $(\delta_i(\Theta_i), \delta_j(\Theta_j))$, and disclosed information, $(\widetilde{\delta}_i, \widetilde{\delta}_j)$. We focus attention to development investments under the "vaporware" disclosure rule, $(\underline{\delta}_i, \overline{\delta}_i) = (\underline{\theta}, \varnothing)$ for $i = 1, 2$. Firms' incentives to invest in development under vaporware are driven solely by the strategic effect. The comparison between development investments under mandated and voluntary disclosure changes because there are no longer two conflicting effects for an uninformed firm under voluntary disclosure. The direct effect, that increases a rival's expected cost from concealment, vanishes under IID. Only the indirect effect, that makes a rival expect a stronger development competitor, remains.

First we introduce the following notation: firm i who received signal Θ_i and received messages $(\widetilde{\delta}_i, \widetilde{\delta}_j)$, with $\widetilde{\delta}_i = \delta_i(\Theta_i)$, invests $D_i^*(\Theta_i; \widetilde{\delta}_i, \widetilde{\delta}_j)$ in equilibrium. We distinguish three different situations for firms. Either both firms disclose, only one firm discloses, or both firms do not disclose information. We discuss firms' equilibrium development investments in these situations in the remainder of this subsection.

When both firms have low development costs, they disclose this cost information. They therefore invest in development as under mandated disclosure, i.e. $D_i^*(\underline{\theta}; \underline{\theta}, \underline{\theta}) = \widehat{D}_i(\underline{\theta}, \underline{\theta})$.

The second case is one in which firm i discloses low costs, while firm j discloses no information: $(\widetilde{\delta}_i, \widetilde{\delta}_j) = (\underline{\theta}, \varnothing)$. In that case firm j could either be a high-cost firm, or an uninformed firm. Given vaporware disclosure, firm i assigns belief $\frac{(1-p)r_j}{1-pr_j}$ to facing a high-cost firm j, and maximizes its expected development profits. This gives first-order condition:

$$\underline{\theta} D_i = W - \Delta \left(\frac{1-r_j}{1-pr_j} D_j(\varnothing) + \frac{(1-p)r_j}{1-pr_j} D_j(\overline{\theta}) \right).$$

Firm j has complete information about costs, and its investments follow the following first-order conditions:

$$\begin{aligned} E(\theta) D_j(\varnothing) &= W - \Delta D_i \\ \overline{\theta} D_j(\overline{\theta}) &= W - \Delta D_i. \end{aligned}$$

Note that $E(\theta)D_j(\varnothing) = \overline{\theta} D_j(\overline{\theta})$. When we substitute this in firm i's first-order condition, and define β_j as:

$$\beta_j \equiv \frac{(1-p)r_j}{1-pr_j} E(\theta) + \frac{1-r_j}{1-pr_j} \overline{\theta},$$

we can easily derive the following equilibrium development investments:

$$\begin{aligned} D_i^*(\underline{\theta}; \underline{\theta}, \varnothing) &= \frac{\left(E(\theta)\overline{\theta} - \beta_j \Delta\right) W}{\underline{\theta} E(\theta) \overline{\theta} - \beta_j \Delta^2}, \\ D_j^*(\varnothing; \varnothing, \underline{\theta}) &= \frac{\overline{\theta}(\underline{\theta} - \Delta) W}{\underline{\theta} E(\theta) \overline{\theta} - \beta_j \Delta^2}, \\ D_j^*(\overline{\theta}; \varnothing, \underline{\theta}) &= \frac{E(\theta)(\underline{\theta} - \Delta) W}{\underline{\theta} E(\theta) \overline{\theta} - \beta_j \Delta^2}. \end{aligned}$$

Note that firm j invests less when it received bad news, and firm j always invests less than firm i in this equilibrium. After information $(\underline{\theta}, \varnothing)$ is disclosed, firms know that firm i has lower expected marginal costs of development than firm j. This encourages firm i, and discourages firm j to invest in development.

Since β_j is decreasing in r_j, it is easily verified that $D_i^*(\underline{\theta}; \underline{\theta}, \varnothing)$ is increasing in r_j, while both $D_j^*(\varnothing; \varnothing, \underline{\theta})$ and $D_j^*(\overline{\theta}; \varnothing, \underline{\theta})$ are decreasing in r_j. When firm j's expected research investments increase, it is more likely that it is informed. More weight is therefore put on competing with a high cost firm j after it sends an uninformative message. This encourages firm i, which, in turn, discourages firm j in the development stage of the race. In particular, when firm j is expected to be uninformed, $r_j = 0$, firms invest their full disclosure amounts $\widehat{D}_i(\underline{\theta}, \varnothing)$ and $\widehat{D}_j(\varnothing, \underline{\theta})$, respectively. When firm j is expected to be fully informed, $r_j = 1$, firms invest in equilibrium $\widehat{D}_i(\underline{\theta}, \overline{\theta})$ and $\widehat{D}_j(\overline{\theta}, \underline{\theta})$, respectively. For expected research investment levels strictly between zero and one, firm i invests strictly between the mandated disclosure development levels: $\widehat{D}_i(\underline{\theta}, \varnothing) < D_i^*(\underline{\theta}; \underline{\theta}, \varnothing) < \widehat{D}_i(\underline{\theta}, \overline{\theta})$ for $0 < r_j < 1$. For $0 < r_j < 1$, informed firm j invests more in development under vaporware, $D_j^*(\overline{\theta}; \varnothing, \underline{\theta}) > \widehat{D}_j(\overline{\theta}, \underline{\theta})$, while uninformed firm j invests less, $D_j^*(\varnothing; \varnothing, \underline{\theta}) < \widehat{D}_j(\varnothing, \underline{\theta})$. Under vaporware informed firm j pools with its uninformed counterpart, which discourages firm i's development investments, and consequently encourages firm j to invest. When firm j is actually uninformed and pools with his high cost counterpart, this encourages its rival and discourages firm j to invest in further development of the innovation.

Finally we consider the case in which both firms disclose no information: $(\widetilde{\delta}_i, \widetilde{\delta}_j) = (\varnothing, \varnothing)$. This gives first-order conditions:

$$\begin{aligned} E(\theta)D_i(\varnothing) &= W - \Delta\left(\frac{1-r_j}{1-pr_j}D_j(\varnothing) + \frac{(1-p)r_j}{1-pr_j}D_j(\overline{\theta})\right) \\ \overline{\theta}D_i(\overline{\theta}) &= W - \Delta\left(\frac{1-r_j}{1-pr_j}D_j(\varnothing) + \frac{(1-p)r_j}{1-pr_j}D_j(\overline{\theta})\right), \end{aligned}$$

for $i, j = 1, 2$ and $i \neq j$. Again this gives $E(\theta)D_i(\varnothing) = \overline{\theta}D_i(\overline{\theta})$, and equilibrium development investments:

$$\begin{aligned} D_i^*(\varnothing; \varnothing, \varnothing) &= \frac{\overline{\theta}\left(E(\theta)\overline{\theta} - \beta_j\Delta\right)W}{E(\theta)^2\overline{\theta}^2 - \beta_i\beta_j\Delta^2}, \\ D_i^*(\overline{\theta}; \varnothing, \varnothing) &= \frac{E(\theta)\left(E(\theta)\overline{\theta} - \beta_j\Delta\right)W}{E(\theta)^2\overline{\theta}^2 - \beta_i\beta_j\Delta^2}, \end{aligned}$$

for $i = 1, 2$, and $i \neq j$. Note that $D_i^*(\overline{\theta}; \varnothing, \varnothing) < D_i^*(\varnothing; \varnothing, \varnothing)$. An uninformed firm is more optimistic about its development costs, and therefore invests more in equilibrium.

When firm j's expected research investments increase, it seems more likely that it is a firm with bad information. This encourages firm i to invest in development. Therefore firm i's development investments are decreasing in r_j. It is intuitive that: $\widehat{D}_i(\Theta_i, \varnothing) \leq D_i^*(\Theta_i; \varnothing, \varnothing) \leq \widehat{D}_i(\Theta_i, \overline{\theta})$ for $\Theta_i \in \{\varnothing, \overline{\theta}\}$, with $D_i^*(\varnothing; \varnothing, \varnothing) = \widehat{D}_i(\varnothing, \varnothing)$ for $r_i = r_j = 0$, and $D_i^*(\overline{\theta}; \varnothing, \varnothing) = \widehat{D}_i(\overline{\theta}, \overline{\theta})$ for $r_i = r_j = 1$.

Expected equilibrium development profits, given disclosed information $(\widetilde{\delta}_i, \widetilde{\delta}_j)$ and equilibrium beliefs are:

$$\pi_i^*(\Theta_i; \widetilde{\delta}_i, \widetilde{\delta}_j) = \frac{1}{2}\theta_i^E(\Theta_i)D_i^*(\Theta_i; \widetilde{\delta}_i, \widetilde{\delta}_j)^2,$$

for $i, j = 1, 2$ and $i \neq j$. We summarize the findings of this subsection in the following lemma:

Lemma 4.3 *For IID take* $(\underline{\delta}, \overline{\delta}) = (\underline{\theta}, \varnothing)$, $r_i = r_j = r$ *and* $i = 1, 2$, $i \neq j$.
(i) For $0 < r < 1$, *vaporware development investments under different states of nature are ordered as follows:*
(i.a)

$$\begin{aligned} D_i^*(\overline{\theta}; \varnothing, \underline{\theta}) &< D_i^*(\varnothing; \varnothing, \underline{\theta}) < D_i^*(\underline{\theta}; \underline{\theta}, \underline{\theta}) < D_i^*(\underline{\theta}; \underline{\theta}, \varnothing), \text{ and} \\ D_i^*(\overline{\theta}; \varnothing, \underline{\theta}) &< D_i^*(\overline{\theta}; \varnothing, \varnothing) < D_i^*(\varnothing; \varnothing, \varnothing) < D_i^*(\underline{\theta}; \underline{\theta}, \varnothing); \end{aligned}$$

(i.b)

$$\begin{aligned} \frac{\partial D_i^*(\Theta_i; \delta_i(\Theta_i), \underline{\theta})}{\partial r_j} &< 0 \text{ for } \Theta_i \in \{\varnothing, \overline{\theta}\}, \text{ and} \\ \frac{\partial D_i^*(\Theta_i; \delta_i(\Theta_i), \varnothing)}{\partial r_j} &> 0 \text{ for } \Theta_i \in \{\underline{\theta}, \varnothing, \overline{\theta}\}; \end{aligned}$$

(ii) Development investments under vaporware compare with those under mandated disclosure as follows:
(ii.a)

$$\begin{aligned} \widehat{D}_i(\Theta_i, \varnothing) &\leq D_i^*(\Theta_i; \delta_i^*(\Theta_i), \varnothing) \leq \widehat{D}_i(\Theta_i, \overline{\theta}), \text{ for } \Theta_i \in \{\underline{\theta}, \varnothing, \overline{\theta}\}, \\ D_i^*(\underline{\theta}; \underline{\theta}, \underline{\theta}) &= \widehat{D}_i(\underline{\theta}, \underline{\theta}),\ D_i^*(\varnothing; \varnothing, \underline{\theta}) \leq \widehat{D}_i(\varnothing, \underline{\theta}), \text{ and } D_i^*(\overline{\theta}; \varnothing, \underline{\theta}) \geq \widehat{D}_i(\overline{\theta}, \underline{\theta}); \end{aligned}$$

(ii.b) For $r = 0$:

$$\begin{aligned} D_i^*(\Theta_i; \Theta_i, \widetilde{\delta}_j) &= \widehat{D}_i(\Theta_i, \widetilde{\delta}_j) \text{ with } \Theta_i, \widetilde{\delta}_j \in \{\underline{\theta}, \varnothing\}, \\ D_i^*(\overline{\theta}; \varnothing, \widetilde{\delta}_j) &= \frac{E(\theta)}{\overline{\theta}} \widehat{D}_i(\overline{\theta}, \widetilde{\delta}_j) \text{ with } \widetilde{\delta}_j \in \{\underline{\theta}, \varnothing\}, \text{ ánd} \end{aligned}$$

for $r = 1$:

$$\begin{aligned} D_i^*(\Theta_i; \delta_i(\Theta_i), \delta_j(\Theta_j)) &= \widehat{D}_i(\Theta_i, \Theta_j) \text{ with } \Theta_i, \Theta_j \in \{\underline{\theta}, \overline{\theta}\}, \\ D_i^*(\varnothing; \varnothing, \delta_j(\Theta_j)) &= \frac{\overline{\theta}}{E(\theta)} \widehat{D}_i(\overline{\theta}, \Theta_j) \text{ with } \Theta_j \in \{\underline{\theta}, \overline{\theta}\}. \end{aligned}$$

Equilibrium Disclosure: "Vaporware"

In this subsection we show that strategic preannouncements are made in equilibrium. Disclosure of only low development costs leaves the rival's expected development cost unaffected, while it makes him expect strong competition in the development stage. The strategic effect is the only effect that drives the result.

Firms anticipate equilibrium development investments when they determine their disclosure rules. Firm i's expected profits under vaporware are the following:

$$E_{\widetilde{\delta}_j}\left\{\pi_i^*(\Theta_i;\widetilde{\delta}_i,\widetilde{\delta}_j)\right\} = pr_j\pi_i^*(\Theta_i;\delta_i(\Theta_i),\underline{\theta}) + (1-pr_j)\pi_i^*(\Theta_i;\delta_i(\Theta_i),\varnothing),$$

for $i = 1, 2$. We prove the following proposition (see Appendix).

Proposition 4.7 *Under IID there is an equilibrium in which firms only disclose low cost information, i.e. they conceal high costs:* $(\underline{\delta}_i^*, \overline{\delta}_i^*) = (\underline{\theta}, \varnothing)$, *for* $i = 1, 2$.

Note that the equilibrium disclosure rule under IID is the complete opposite of the equilibrium rule under PPC. Since there no is no longer an informational effect of disclosure, the result is completely driven by the strategic effect of disclosure. By preannouncing good news about your costs of development investment, you disclose yourself as a tough competitor in the development stage of the race. This discourages your rival's development investments. And since there is only one effect that drives this result, it holds for all parameter values. Remember that under PPC the informational effect is the dominating effect for most parameter values. However, we could find some extreme, asymmetric parameter value combinations under PPC for which the strategic effect dominated for a firm.

Equilibrium Research Investments

In this subsection we show that there are parameter values for which equilibrium research investments under vaporware disclosure exceed those under mandated disclosure. The intuition for this result is the following. If a firm j receives good news, $\Theta_j = \underline{\theta}$, then firm i expects under voluntary disclosure relatively higher profit from being informed, and lower from remaining uninformed. This gives it an incentive to acquire information. When firm j does not voluntarily disclose information, $\widetilde{\delta}_j = \varnothing$, firm i faces the following trade-off. When firm i would acquire low or no cost information, $\Theta_i \in \{\underline{\theta}, \varnothing\}$, it would be better off under mandated disclosure. The first observation gives the firm a disincentive to acquire information, while the second gives the firm an incentive to acquire more information under voluntary disclosure. If firm i would acquire bad news, $\Theta_i = \overline{\theta}$, its development equilibrium profit under voluntary disclosure would exceed that expected equilibrium profit under mandated disclosure. This increases the firm's incentive to acquire information under voluntary disclosure.

The relative disincentive of information acquisition under voluntary disclosure is outweighed by the two extra incentives, if the spread between high and low cost is not too big.

Before the firms choose their disclosure rules, they invest in research. Firm i's first-order condition of maximizing expected profit toward R_i, after expectations are realized, is:

$$\begin{aligned} \rho R_i &= pR_j \left\{ E_{\theta_i} \left(\pi_i^*(\theta_i; \delta_i^*(\theta_i), \underline{\theta}) \right) - \pi_i^*(\varnothing; \varnothing, \underline{\theta}) \right\} + \\ &\quad + (1 - pR_j) \left\{ E_{\theta_i} \left(\pi_i^*(\theta_i; \delta_i^*(\theta_i), \varnothing) \right) - \pi_i^*(\varnothing; \varnothing, \varnothing) \right\}. \end{aligned}$$

We can prove the following proposition:

Proposition 4.8 *For IID and any p, W, Δ and $\underline{\theta}$ there is an $\varepsilon > 0$, such that if $\overline{\theta} \in (\underline{\theta}, \underline{\theta}+\varepsilon]$, firms' equilibrium research investments under voluntary disclosure exceed those under mandated disclosure, i.e. $R_i^* \geq \widehat{R}_i$ for $i = 1, 2$. This holds with strict inequality for interior equilibrium research investments.*

Actually, ε can be rather big. For example, for $p = \frac{1}{2}$, $\Delta = \frac{1}{2}$, $\underline{\theta} = 2$ and $\overline{\theta} = 200$ firms invest more in research under voluntary disclosure then under mandated disclosure.

Conclusion (IID)

In this subsection we have seen that firms' incentives to disclose information are drastically changed in comparison to a race with perfect positive correlation between development costs. Under PPC firms have an incentive to only disclose bad news to make their rival pessimistic about costs of development, while under IID firms discourage their rival by disclosing good news about themselves. While under PPC the informational effect dominates, under IID the strategic effect rules. Obviously, not only is the equilibrium disclosure rule affected, but also the firms' equilibrium investments in R&D are affected. Generically firms overinvest in both research and development under mandated disclosure, while they invest yet more in research under voluntary disclosure.

4.5 Conclusion

In this chapter we developed a theory of information acquisition, strategic disclosure and product development in a dynamic competitive setting. We have seen that disclosure regulation substantially affects firms' investments, both in research as well as in development. And finally we have shown that correlation between development costs affect equilibrium disclosure and investments dramatically.

We have given a model in which "vaporware" emerges in equilibrium. We have seen that Microsoft's alleged strategic preannouncements, and British Biotech's attempted concealment can be explained in a dynamic, strategic setting of incomplete information. Furthermore we have been able to explain how firm's investments are affected in the different regimes. In another extreme of the model we have shown how to explain the increased competition after IBM's breakthrough in the research of superconductivity. Not only did we replicate Choi's (1991) results, but we could also indicate in what direction equilibrium investments change when disclosure is no longer mandated, and when costs are not perfectly correlated.

The analysis of this chapter can be extended in many directions. It would be interesting to study the effects of introducing revenue sharing in this model. This could correct some of the equilibrium inefficiencies as the previous chapter suggested. A natural next step would be to study how results change for intermediate degrees of correlations. For intermediate degrees of correlation we would expect a more subtle trade-off between the informational and strategic effect of information disclosure. In the race with identical independently distributed development cost new insights could be gained when we study the effects of knowledge spillovers. If part of the innovation's contents are revealed after its preannouncements, this could make firms more reluctant to preannounce innovations. These extensions of the basic analysis await future research.

4.6 Appendix

This Appendix contains proofs to the main propositions of this chapter. The Appendix is organized as follows. The first two subsections contain proofs to the results under PPC. The first subsection proves underinvestment in research investments under mandated disclosure. In the second subsection we prove results under voluntary disclosure. The third subsection of the Appendix provides proofs for the model under IID.

4.6.1 PPC: Mandated Disclosure, Proposition 4.1

Part (i) of the proposition is obvious. For part (ii) we have to show that $\frac{B}{\rho+B} < \frac{A}{\rho+A}$. Since $\rho > 0$, and the function $F(x) = \frac{x}{\rho+x}$ is increasing in x, it suffices to show that

$A > B$. Decompose B as follows:

$$\begin{aligned}\frac{2B}{W^2} &= \left(\frac{p}{\underline{\theta}+\Delta}+\frac{1-p}{\overline{\theta}+\Delta}-\frac{1}{E(\theta)+\Delta}\right)+\\ &\quad -\Delta\left(\frac{p}{(\underline{\theta}+\Delta)^2}+\frac{1-p}{(\overline{\theta}+\Delta)^2}-\frac{1}{(E(\theta)+\Delta)^2}\right)\end{aligned}$$

and note that

$$\frac{A-2B}{W^2}=\Delta\left(\frac{p}{(\underline{\theta}+\Delta)^2}+\frac{1-p}{(\overline{\theta}+\Delta)^2}-\frac{1}{(E(\theta)+\Delta)^2}\right)+$$

$$-\Delta\left(\frac{p}{(\underline{\theta}+\Delta)(\underline{\theta}+2\Delta)}+\frac{1-p}{(\overline{\theta}+\Delta)(\overline{\theta}+2\Delta)}-\frac{1}{(E(\theta)+\Delta)(E(\theta)+2\Delta)}\right)$$

$$=\Delta^2\left(\frac{p}{(\underline{\theta}+\Delta)^2(\underline{\theta}+2\Delta)}+\frac{1-p}{(\overline{\theta}+\Delta)^2(\overline{\theta}+2\Delta)}-\frac{1}{(E(\theta)+\Delta)^2(E(\theta)+2\Delta)}\right)$$

which is positive, since $g(\theta)\equiv\frac{1}{(\theta+\Delta)^2(\theta+2\Delta)}$ is convex in θ, and therefore $E\left(g(\theta)\right) > g\left(E(\theta)\right)$. This proves the proposition.

4.6.2 PPC: Voluntary Disclosure

In this subsection we prove the main results concerning equilibrium choices of firms who voluntarily disclose information. First we characterize development investments under partial disclosure. Second we give a negative result. We show that neither full disclosure, nor full concealment, nor partial disclosure with only disclosure of good news can be equilibrium disclosure rules. Third we derive the sufficient condition under which firms always partially disclose information. Then we show that equilibrium research investments under voluntary disclosure, exceed those under mandated disclosure. Finally we derive necessary and sufficient conditions under which firms partially disclosure their intermediate information in equilibrium. This is done in the next five subsections.

Proof of Proposition 4.2

First we calculate equilibrium development investments under partial disclosure. We substitute the equation (4.1) in equation (4.2). This transforms the uninformed firm's reaction into:

$$pE_i^*(\theta|\varnothing)D_i^*(\varnothing)=pW-\alpha_j\left(W-\underline{\theta}D_i^*(\underline{\theta})\right)+(1-p)r_j\alpha_jD_j^*(\underline{\theta})\Delta.$$

Substituting this expression in the low-signal firm's reaction function, equation (4.1), results in the following "reduced-form" reaction function:

$$D_i^*(\underline{\theta}) = \frac{\left(\theta_j^* + (1-p)r_i(1-r_j)\Delta\right) W - \left(r_j\theta_j^* + (1-r_j)\underline{\theta}\right) D_j^*(\underline{\theta})\Delta}{\left(\underline{\theta}\theta_j^* + (1-p)r_i(1-r_j)\Delta^2\right)} \tag{4.6}$$

for $i, j = 1, 2$ ($i \neq j$), with $\theta_j^* = p\underline{\theta} + (1-p)(1-r_i)\overline{\theta}$. When we follow a similar procedure for the uninformed firms, we rewrite:

$$\alpha_j\underline{\theta}D_i^*(\underline{\theta}) = \alpha_j W - (W - E_i^*(\theta|\varnothing)D_i^*(\varnothing)) + \frac{(1-p)(1-r_j)}{pr_j + 1 - r_j}D_j^*(\varnothing)\Delta.$$

After substituting this in uninformed firm i's reaction function, equation (4.2), this gives his "reduced-form" reaction function:

$$D_i^*(\varnothing) = \frac{\left(\underline{\theta}(1-r_j+pr_j) + (1-p)(1-r_i)r_j\Delta\right) W - \left(r_j\theta_j^* + (1-r_j)\underline{\theta}\right) D_j^*(\varnothing)\Delta}{\left(\underline{\theta}\theta_i^* + (1-p)(1-r_i)r_j\Delta^2\right)}, \tag{4.7}$$

for $i, j = 1, 2$ ($i \neq j$). From the "reduced-form" reaction functions we can derive the equilibrium development investments.

(i) After calculating the equilibrium development investments, we note that $D_i^*(\varnothing) - D_j^*(\varnothing)$ is proportional to $p(1-p)\underline{\theta}W(\underline{\theta}-\Delta)(\overline{\theta}-\underline{\theta})(r_j - r_i)$, which provides the characterization directly.

(ii) For $r_i = r_j$ equilibrium development investments follow directly from the "reduced-form" reaction functions. Comparisons between investment levels are straightforward. This completes the proof.

Proof of Lemma 4.1

(i) Disclosure rule $(\underline{\delta}, \overline{\delta}) = (\underline{\theta}, \overline{\theta})$ gives full disclosure of information. Consequently, firms i's development investments are $\widehat{D}_i(\underline{\theta})$, $\widehat{D}_i(\varnothing)$ and $\widehat{D}_i(\overline{\theta})$, with $i = 1, 2$. Take $r_j < 1$, and suppose full disclosure can be sustained as an equilibrium. Then the equilibrium development investments are as in the previous section. But when low-cost firm i anticipates these investments, it has an incentive to conceal its information. Given equilibrium beliefs, disclosure choice $\delta_i(\underline{\theta}) = \varnothing$ only affects investments when firm j is uninformed, which happens with positive probability ($r_j < 1$). An uninformed firm j who receives message $\widetilde{\delta}_i = \varnothing$ from its rival invests $\widehat{D}_j(\varnothing)$, which is less than the investment $\widehat{D}_j(\underline{\theta})$ after disclosure of $\Theta_i = \underline{\theta}$. Given $r_j < 1$, firm j's expected development investments are:

$$r_j\widehat{D}_j(\underline{\theta}) + (1-r_j)\widehat{D}_j(\varnothing) < \widehat{D}_j(\underline{\theta}).$$

Therefore firm i's optimal deviation investment, and consequently its expected deviation profit, is bigger than in the proposed equilibrium. Consequently full disclosure cannot be sustained as an equilibrium.

(ii) Intuitive given (i) and (iii).

(iii) Disclosure rule $(\underline{\delta}, \overline{\delta}) = (\varnothing, \varnothing)$ discloses no information about cost signals. In this case firms do not update their beliefs after disclosure. They can only condition their development investments on their own observed cost signal. Firm i invests $D_i^o(\underline{\theta})$, $D_i^o(\varnothing)$ and $D_i^o(\overline{\theta})$ in development after receiving $\Theta_i = \underline{\theta}$, $\varnothing$ and $\overline{\theta}$, respectively. These investments are determined by the following first-order conditions:

$$\begin{aligned}
\underline{\theta} D_i^o(\underline{\theta}) &= W - \left(r_j D_j^o(\underline{\theta}) + (1-r_j) D_j^o(\varnothing)\right)\Delta \\
\overline{\theta} D_i^o(\overline{\theta}) &= W - \left(r_j D_j^o(\overline{\theta}) + (1-r_j) D_j^o(\varnothing)\right)\Delta \\
E(\theta) D_i^o(\varnothing) &= W - \left(r_j p D_j^o(\underline{\theta}) + r_j(1-p) D_j^o(\overline{\theta}) + (1-r_j) D_j^o(\varnothing)\right)\Delta
\end{aligned}$$

Note that $E(\theta)D_i^o(\varnothing) = p\underline{\theta}D_i^o(\underline{\theta}) + (1-p)\overline{\theta}D_i^o(\overline{\theta})$. Given these investments and beliefs we can show that a firm with signal $\Theta_i = \overline{\theta}$ has an incentive to disclose its information. If the high-signal firm i would choose investments $D_i^o(\overline{\theta})$ it would receive an expected profit of $\frac{1}{2}\overline{\theta}D_i^o(\overline{\theta})^2$. When this firm discloses its information it gets $\frac{1}{2}\overline{\theta}\widehat{D}_i(\overline{\theta})^2$. Deviating from concealment is therefore profitable whenever $D_i^o(\overline{\theta}) < \widehat{D}_i(\overline{\theta}) = \frac{W}{\overline{\theta}+\Delta}$. We use expression

$$E(\theta)D_i^o(\varnothing) = p\underline{\theta}D_i^o(\underline{\theta}) + (1-p)\overline{\theta}D_i^o(\overline{\theta})$$

to reduce the development equilibrium conditions under no-disclosure to the following system of equations:

$$\begin{aligned}
\underline{\theta} D_i^o(\underline{\theta}) &= W - \left(r_j + \frac{1-r_j}{E(\theta)} p\underline{\theta}\right) D_j^o(\underline{\theta})\Delta - \frac{1-r_j}{E(\theta)}(1-p)\overline{\theta}D_j^o(\overline{\theta})\Delta \\
&= W - \left(\frac{r_j}{p\underline{\theta}} + \frac{1-r_j}{E(\theta)}\right)\left(p\underline{\theta}D_j^o(\underline{\theta}) + (1-p)\overline{\theta}D_j^o(\overline{\theta})\right)\Delta + \\
&\quad + \frac{r_j(1-p)\overline{\theta}}{p\underline{\theta}} D_j^o(\overline{\theta})\Delta \\
\overline{\theta} D_i^o(\overline{\theta}) &= W - r_j D_j^o(\overline{\theta})\Delta - \frac{1-r_j}{E(\theta)}\left(p\underline{\theta}D_j^o(\underline{\theta}) + (1-p)\overline{\theta}D_j^o(\overline{\theta})\right)\Delta.
\end{aligned}$$

After substituting the second equation into the first, we write the low-signal firm i's optimal development investments as a function of firms' high-signal investments only:

$$\begin{aligned}
(1-r_j)p\underline{\theta}^2 E(\theta) D_i^o(\underline{\theta}) &= -r_j E(\theta) W + r_j E(\theta) D_j^o(\overline{\theta})\Delta + \\
&\quad + \left(r_j E(\theta) + (1-r_j)p\underline{\theta}\right)\overline{\theta}D_i^o(\overline{\theta}).
\end{aligned}$$

When we substitute this expression back in the second equation of the system, we get the high-signal firm's "reduced-form" reaction function. When this function does not intersect with the set $\{D \in [0,1]^2 | D_i \geq \frac{W}{\overline{\theta}+\Delta}\}$, any equilibrium investment $D_i^o(\overline{\theta})$ is smaller than $\widehat{D}_i(\overline{\theta})$. Since the "reduced-form" reaction function slopes downward, it suffices to show that a firm's optimal reaction to rival's investment $\widehat{D}_j(\overline{\theta})$ under concealment is smaller than $\widehat{D}_i(\overline{\theta})$. When we substract $\widehat{D}_j(\overline{\theta})$ from firm i's "reduced-form" reaction to $\widehat{D}_j(\overline{\theta})$, we obtain:

$$\frac{-p\Delta\underline{\theta}(1-r_i)(1-r_j)(\overline{\theta}-\underline{\theta})W}{(\overline{\theta}+\Delta)E(\theta)\left((1-r_i)\underline{\theta}\overline{\theta}+r_i(1-r_j)\Delta^2\right)} \leq 0.$$

Since this is negative for all $(r_i, r_j) < (1,1)$, unilaterally disclosing $\overline{\theta}$ is profitable for firm i. This completes the proof.

Proof of Proposition 4.3

The proof to this proposition directly follows from necessary and sufficient conditions (4.4) and (4.5) of proposition 4.5. Observe that the critical values for r_j of these conditions are increasing in r_i. It therefore suffices to evaluate the critical value of condition (4.4) at $r_i = 0$, and find the prior probabilities p for which the critical value exceeds 1. This happens for all p in (4.3). For critical value (4.5) it suffices to evaluate it at r_i, and find the p for which it does not exceed zero. This happens for $p \geq \frac{\Delta}{\underline{\theta}+\Delta}$, which is satisfied under (4.3). This completes the proof.

Proof of Proposition 4.4

Equilibrium research investments under voluntary disclosure are bigger than under mandated disclosure whenever marginal revenues of research under voluntary disclosure exceed marginal revenues under mandated disclosure. Since high-cost firms earn identical development profits under mandated and voluntary disclosure, we can ignore these profit levels in the comparison of marginal revenues. We can rewrite the equilibrium marginal revenues of research under required disclosure, net of high-cost firms' revenues, to:

$$\begin{aligned}\widehat{MR}(R) &\equiv p\frac{1}{2}\underline{\theta}\widehat{D}_i(\underline{\theta})^2 - \frac{1}{2}\left(p\underline{\theta}+(1-p)(1-R_j)\overline{\theta}\right)\widehat{D}_i(\varnothing)^2 + \\ &\quad -pR_j\frac{1}{2}\underline{\theta}\left(\widehat{D}_i(\underline{\theta})^2 - \widehat{D}_i(\varnothing)^2\right).\end{aligned}$$

Equilibrium marginal revenues of research under voluntary disclosure, net of high-cost firms' revenues, are:

$$MR^*(R) \equiv p\frac{1}{2}\underline{\theta}D_i^*(\underline{\theta})^2 - \frac{1}{2}\left(p\underline{\theta} + (1-p)(1-R_j)\overline{\theta}\right)D_i^*(\varnothing)^2.$$

Since we focus on symmetric research equilibria, we take $R_i = R_j = R$. We must check that for all R:

$$\begin{aligned} MR^*(R) - \widehat{MR}(R) &= p\frac{1}{2}\underline{\theta}\left(D_i^*(\underline{\theta})^2 - \widehat{D}_i(\underline{\theta})^2\right) + pR\frac{1}{2}\underline{\theta}\left(\widehat{D}_i(\underline{\theta})^2 - \widehat{D}_i(\varnothing)^2\right) \\ &\quad -\frac{1}{2}\left(p\underline{\theta} + (1-p)(1-R)\overline{\theta}\right)\left(D_i^*(\varnothing)^2 - \widehat{D}_i(\varnothing)^2\right) \end{aligned}$$

exceeds zero. We already know that $D_i^*(\underline{\theta}) > \widehat{D}_i(\underline{\theta})$. Define the following function:

$$G(R) \equiv \frac{1}{2}\left(p\underline{\theta} + (1-p)(1-R)\overline{\theta}\right)\left(D_i^*(\varnothing)^2 - \widehat{D}_i(\varnothing)^2\right) - pR\frac{1}{2}\underline{\theta}\left(\widehat{D}_i(\underline{\theta})^2 - \widehat{D}_i(\varnothing)^2\right).$$

Now we only need to show that $G(R) \leq 0$ for all R. Observe that for $R = 0$, $D_i^*(\varnothing) = \widehat{D}_i(\varnothing)$, which makes $G(0) = 0$. For $R = 1$, $D_i^*(\varnothing) = \widehat{D}_i(\underline{\theta})$, which implies that $G(1) = 0$. Therefore, for $G(R) \leq 0$ for all $R \in (0,1)$, it suffices to show that G is convex in R. Note that:

$$\begin{aligned} G''(R) &= \frac{1}{2} \cdot \frac{d^2}{dR^2}\left\{\left(p\underline{\theta} + (1-p)(1-R)\overline{\theta}\right)D_i^*(\varnothing)^2\right\} \\ &= D_i^*(\varnothing)\left\{\left(p\underline{\theta} + (1-p)(1-R)\overline{\theta}\right)\frac{d^2D_i^*(\varnothing)}{dR^2} - 2(1-p)\overline{\theta}\frac{dD_i^*(\varnothing)}{dR}\right\} + \\ &\quad + \left(p\underline{\theta} + (1-p)(1-R)\overline{\theta}\right)\left(\frac{dD_i^*(\varnothing)}{dR}\right)^2. \end{aligned}$$

It is easily verified that:

$$\begin{aligned} &\left(p\underline{\theta} + (1-p)(1-R)\overline{\theta}\right)\frac{d^2D_i^*(\varnothing)}{dR^2} - 2(1-p)\overline{\theta}\frac{dD_i^*(\varnothing)}{dR} \\ = \; &\frac{2W(1-p)p\underline{\theta}(\overline{\theta} - \underline{\theta})\Delta g(R;\overline{\theta})}{\left(p\underline{\theta}(\underline{\theta} + \Delta) + (1-p)(1-R)(\overline{\theta} + \Delta)(\underline{\theta} + R\Delta)\right)^3}, \end{aligned}$$

with

$$\begin{aligned} g(R;\overline{\theta}) \equiv\; &(1-p)^2(1-R)^3\Delta\overline{\theta}^2 + (1-p)(1-R)^2\left(3p\underline{\theta} + (1-p)(1-R)\Delta\right)\Delta\overline{\theta} + \\ &+p\underline{\theta}\left(\underline{\theta}^2 - (1-3R+p(3R-2))\Delta\underline{\theta} + (1-p)(1-3R+3R^2)\Delta^2\right). \end{aligned}$$

Since

$$\frac{\partial g(R;\overline{\theta})}{\partial \overline{\theta}} = (1-p)(1-R)^2\Delta\left((1-p)(1-R)(2\overline{\theta}+\Delta)+3p\underline{\theta}\right) \geq 0,$$

and $\overline{\theta} > \underline{\theta}$, we obtain:

$$g(R;\overline{\theta}) \geq g(R;\underline{\theta}) = \underline{\theta}(\underline{\theta}+\Delta)\left(p\underline{\theta}+(1-p)\Delta(pR^3+(1-R)^3)\right) > 0.$$

Therefore $G''(R) > 0$, which completes the proof.

Proof of Proposition 4.5

Suppose δ^* is the equilibrium disclosure rule. This disclosure rule gives equilibrium development investments $D^*(\underline{\theta})$, $D^*(\varnothing)$ and $D^*(\overline{\theta})$. Consider the two possible deviations from the equilibrium disclosure rule. First, a firm with a low cost signal, $\Theta_i = \underline{\theta}$, can choose to disclose its information. Disclosing low development costs, gives firm i development investments $\widehat{D}_i(\underline{\theta})$ and profits $\frac{1}{2}\underline{\theta}\widehat{D}_i(\underline{\theta})^2$. Concealment of low costs gives expected equilibrium profits $\frac{1}{2}\underline{\theta}D_i^*(\underline{\theta})^2$. Therefore deviation from the equilibrium disclosure rule is not profitable whenever $\widehat{D}_i(\underline{\theta}) \leq D_i^*(\underline{\theta})$. After we solve for the equilibrium investment we obtain:

$$D_i^*(\underline{\theta}) - \widehat{D}_i(\underline{\theta}) = \frac{W(1-p)(\overline{\theta}-\underline{\theta})(1-r_i)(1-r_j)\Delta Z_D^L}{(\underline{\theta}+\Delta)Z_N},$$

with

$$\begin{aligned} Z_N = &\left[p(1-p)\left(r_i(1-r_j)+(1-r_i)r_j\right)\overline{\theta}+p^2(r_i+r_j-r_ir_j)\underline{\theta}\right]\underline{\theta}(\underline{\theta}^2-\Delta^2)+ \\ &+(1-r_i)(1-r_j)\left[\underline{\theta}^2\left((p\underline{\theta}+(1-p)\overline{\theta})^2-\Delta^2\right)-(1-p)^2r_ir_j\Delta^2(\overline{\theta}^2-\Delta^2)\right] \end{aligned}$$

$$\geq (1-r_i)(1-r_j)\left[\underline{\theta}^2\left((p\underline{\theta}+(1-p)\overline{\theta})^2-\Delta^2\right)-(1-p)^2r_ir_j\Delta^2(\overline{\theta}^2-\Delta^2)\right]$$

$$\begin{aligned} = (1-r_i)(1-r_j)&\left[\underline{\theta}^2\left(p^2(\underline{\theta}^2-\Delta^2)+2p(1-p)(\underline{\theta}\overline{\theta}-\Delta^2)\right)+\right. \\ &\left.+(1-p)^2(\overline{\theta}^2-\Delta^2)\left(\underline{\theta}^2-r_ir_j\Delta^2\right)\right] \geq 0, \end{aligned}$$

and

$$Z_D^L = (1-p)(\overline{\theta}-\Delta)\left((1-r_i)\underline{\theta}-r_i(1-r_j)\Delta\right)+p\underline{\theta}(\underline{\theta}-\Delta).$$

Note that $Z_D^L \geq 0$ under condition (4.4).

Second, a firm with a high cost signal, $\Theta_i = \overline{\theta}$, can choose to conceal its information. After disclosing high costs, firm i receives profit $\frac{1}{2}\overline{\theta} D_i^*(\overline{\theta})^2$. After stating $\widetilde{\delta}_i = \varnothing$, high-cost firm i only changes firm j's development investments when $\Theta_j = \varnothing$. In that case firm j chooses investment $D_j^*(\varnothing)$ instead of equilibrium investment $D_j^*(\overline{\theta})$. Consequently firm i's deviation investment and profits are respectively:

$$\overline{\theta}\widetilde{D}_i = W - \left(r_j D_j^*(\overline{\theta}) + (1-r_j) D_j^*(\varnothing)\right)\Delta \text{ and } \widetilde{\pi}_i(\varnothing|\overline{\theta}) = \frac{1}{2}\overline{\theta}\widetilde{D}_i^2.$$

Therefore, when $r_j < 1$ deviation from δ_i^* is not profitable whenever $\widetilde{D}_i \leq D_i^*(\overline{\theta})$, or $D_j^*(\varnothing) \geq D_j^*(\overline{\theta})$. We follow the similar procedure as for the low-signal firms. We rewrite the condition to:

$$D_j^*(\varnothing) - \widehat{D}_j(\overline{\theta}) = \frac{Wp\underline{\theta}(\overline{\theta} - \underline{\theta})Z_D^H}{(\overline{\theta} + \Delta)Z_N} \geq 0,$$

where

$$Z_D^H = p\underline{\theta}(\underline{\theta} - \Delta) + (1-p)[(1-r_j)(\underline{\theta} - r_i\Delta)\overline{\theta} - (1-r_i)(\underline{\theta} - r_j\Delta)\Delta],$$

and $Z_D^H \geq 0$ gives condition (4.5). This completes the proof.

4.6.3 IID: Mandated Disclosure, Proposition 4.6

For the comparison between optimal and equilibrium research investments we need to compare marginal research revenues under total profit maximization and mandated disclosure. We do this in the remainder of the proof for part (i) and (ii) respectively.
(i) Overinvestment in research is obtained when marginal research revenue in equilibrium exceeds marginal revenue under total profit maximization. Define the following function:

$$\begin{aligned} H_i(\theta_i, \theta_j) &\equiv \sum_{\ell=1}^{2} \overline{\pi}_\ell(\theta_i, \theta_j) - \widehat{\pi}_i(\theta_i, \theta_j) \\ &= \frac{W}{2}\left(\frac{\theta_i + \theta_j - 4\Delta}{\theta_i\theta_j - 4\Delta^2} - \frac{\theta_i(\theta_j - \Delta)^2}{(\theta_i\theta_j - \Delta^2)^2}\right) \end{aligned}$$

A sufficient condition for overinvestment by firm i is then that for all R_j:

$$R_j E_{\theta_j}\left\{pH_i(\underline{\theta}, \theta_j) + (1-p)H_i(\overline{\theta}, \theta_j) - H_i(E(\theta), \theta_j)\right\} +$$

$$+(1-R_j)\left\{pH_i(\underline{\theta}, E(\theta)) + (1-p)H_i(\overline{\theta}, E(\theta)) - H_i(E(\theta), E(\theta))\right\} < 0.$$

If function H_i is concave in θ_i for all θ_j, then this sufficient condition is met for any R_j and p. The second-order derivative of H_i towards θ_i is:

$$\frac{\partial^2 H_i(\theta_i,\theta_j)}{\partial\theta_i^2} = W\theta_j\left(\frac{(\theta_j-2\Delta)^2}{(\theta_i\theta_j-4\Delta^2)^3} - \frac{(\theta_j-\Delta)^2(\theta_i\theta_j+2\Delta^2)}{(\theta_i\theta_j-\Delta^2)^4}\right).$$

We evaluate this function in $(\theta_i,\theta_j) = (\widetilde{\theta}_i+3\Delta, \widetilde{\theta}_j+3\Delta)$, with $\widetilde{\theta}_\ell \geq 0$ for $\ell = i,j$, which gives:

$$\begin{aligned}
\left.\frac{\partial^2 H_i(\theta)}{\partial\theta_i^2}\right|_{\theta=\widetilde{\theta}+3\Delta} &= W(\widetilde{\theta}_j+3\Delta)\left(\frac{(\widetilde{\theta}_j+\Delta)^2}{[(\widetilde{\theta}_i+3\Delta)(\widetilde{\theta}_j+3\Delta)-4\Delta^2]^3}+\right.\\
&\quad\left.-\frac{(\widetilde{\theta}_j+2\Delta)^2[(\widetilde{\theta}_i+3\Delta)(\widetilde{\theta}_j+3\Delta)+2\Delta^2]}{[(\widetilde{\theta}_i+3\Delta)(\widetilde{\theta}_j+3\Delta)-\Delta^2]^4}\right)\\
&= \frac{W(\widetilde{\theta}_j+3\Delta)h_i(\widetilde{\theta})}{[(\widetilde{\theta}_i+3\Delta)(\widetilde{\theta}_j+3\Delta)-4\Delta^2]^3[(\widetilde{\theta}_i+3\Delta)(\widetilde{\theta}_j+3\Delta)-\Delta^2]^4},
\end{aligned}$$

with

$$\begin{aligned}
h_i(\widetilde{\theta}) &= (\widetilde{\theta}_j+\Delta)^2[(\widetilde{\theta}_i+3\Delta)(\widetilde{\theta}_j+3\Delta)-\Delta^2]^4+\\
&\quad -(\widetilde{\theta}_j+2\Delta)^2[(\widetilde{\theta}_i+3\Delta)(\widetilde{\theta}_j+3\Delta)+2\Delta^2][(\widetilde{\theta}_i+3\Delta)(\widetilde{\theta}_j+3\Delta)-4\Delta^2]^3\\
&= -\Delta[\widetilde{\theta}_i^4(\widetilde{\theta}_j+3\Delta)^4(2\widetilde{\theta}_j+3\Delta)+2\Delta^2\widetilde{\theta}_i^3(\widetilde{\theta}_j+3\Delta)^3(\widetilde{\theta}_j+2\Delta)+\\
&\quad +2\Delta\widetilde{\theta}_i^2(\widetilde{\theta}_i+3\Delta)(\widetilde{\theta}_j+3\Delta)^3(9\widetilde{\theta}_j^2+36\Delta\widetilde{\theta}_j+32\Delta^2)+\\
&\quad +2\Delta^3\widetilde{\theta}_i(\widetilde{\theta}_j+3\Delta)(27\widetilde{\theta}_j^4+270\Delta\widetilde{\theta}_j^3+999\Delta^2\widetilde{\theta}_j^2+1580\Delta^3\widetilde{\theta}_j+876\Delta^4)\\
&\quad +\Delta^5(27\widetilde{\theta}_j^4+378\Delta\widetilde{\theta}_j^3+1575\Delta^2\widetilde{\theta}_j^2+2564\Delta^3\widetilde{\theta}_j+1404\Delta^4)].
\end{aligned}$$

Since $h_i(\widetilde{\theta}) < 0$ for all $\widetilde{\theta} \geq 0$, function H_i is concave in θ_i, for all $\theta_i, \theta_j \geq 3\Delta$. This completes the proof.

(ii) The prove to research underinvestment is straightforward. This completes the proof.

4.6.4 IID: Voluntary Disclosure

In this subsection of the Appendix we prove the propositions on equilibrium investments under voluntary disclosure. We first prove that vaporware disclosure is indeed an equilibrium disclosure rule. Second we show that equilibrium research investments under voluntary disclosure can be higher than those under mandated disclosure, for $\overline{\theta}$ close enough to $\underline{\theta}$.

Proof of Proposition 4.7

Distinguish two deviations from the "vaporware" equilibrium. First, consider a $\overline{\theta}$-firm i. In equilibrium it receives expected profits:

$$E_{\widetilde{\delta}_j}\left\{\pi_i^*(\overline{\theta};\varnothing,\widetilde{\delta}_j)\right\}=\frac{1}{2}\overline{\theta}\left(pr_jD_i^*(\overline{\theta};\varnothing,\underline{\theta})^2+(1-pr_j)D_i^*(\overline{\theta};\varnothing,\varnothing)^2\right).$$

It could, however, unilaterally choose to disclose its costs. It would then receive expected profits:

$$E_{\widetilde{\delta}_j}\left\{\pi_i(\overline{\theta};\overline{\theta},\widetilde{\delta}_j)\right\}=\frac{1}{2}\overline{\theta}\left(pr_j\widehat{D}_i(\overline{\theta},\underline{\theta})^2+(1-pr_j)\widetilde{D}_i(\overline{\theta};\overline{\theta},\varnothing)^2\right),$$

where $\widetilde{D}_i(\overline{\theta};\overline{\theta},\varnothing)$ solves

$$\begin{aligned}
\overline{\theta}D_i &= W-\Delta\left(\frac{1-r_j}{1-pr_j}D_j(\varnothing)+\frac{(1-p)r_j}{1-pr_j}D_j(\overline{\theta})\right)\\
E(\theta)D_j(\varnothing) &= W-\Delta D_i\\
\overline{\theta}D_j(\overline{\theta}) &= W-\Delta D_i,
\end{aligned}$$

and is therefore

$$\widetilde{D}_i(\overline{\theta};\overline{\theta},\varnothing)=\frac{\left(E(\theta)\overline{\theta}-\beta_j\right)W}{\left(E(\theta)\overline{\theta}^2-\beta_j\Delta^2\right)}.$$

It is straightforward to verify that $D_i^*(\overline{\theta};\varnothing,\underline{\theta})>\widehat{D}_i(\overline{\theta},\underline{\theta})$ and $D_i^*(\overline{\theta};\varnothing,\varnothing)>\widetilde{D}_i(\overline{\theta};\overline{\theta},\varnothing)$. And, therefore, $E_{\widetilde{\delta}_j}\left\{\pi_i^*(\overline{\theta};\varnothing,\widetilde{\delta}_j)\right\}>E_{\widetilde{\delta}_j}\left\{\pi_i^*(\overline{\theta};\overline{\theta},\widetilde{\delta}_j)\right\}$. Secondly, a $\underline{\theta}$-firm i should not have an incentive to conceal its costs. Expected equilibrium profit from disclosure is:

$$E_{\widetilde{\delta}_j}\left\{\pi_i^*(\underline{\theta};\underline{\theta},\widetilde{\delta}_j)\right\}=\frac{1}{2}\underline{\theta}\left(pr_jD_i^*(\underline{\theta};\underline{\theta},\underline{\theta})^2+(1-pr_j)D_i^*(\underline{\theta};\underline{\theta},\varnothing)^2\right),$$

while expected profit from concealment is maximized for $\underline{\theta}D_i(\underline{\theta};\varnothing,\widetilde{\delta}_j)=\overline{\theta}D_i^*(\overline{\theta};\varnothing,\widetilde{\delta}_j)$, with $\widetilde{\delta}_j\in\{\underline{\theta},\varnothing\}$. This gives expected deviation profit of:

$$E_{\widetilde{\delta}_j}\left\{\pi_i^*(\underline{\theta};\varnothing,\widetilde{\delta}_j)\right\}=\frac{\overline{\theta}^2}{2\underline{\theta}}\left(pr_jD_i^*(\overline{\theta};\varnothing,\underline{\theta})^2+(1-pr_j)D_i^*(\overline{\theta};\varnothing,\varnothing)^2\right).$$

The deviation for $\underline{\theta}$-firm i is unprofitable because $\underline{\theta}D_i^*(\underline{\theta};\underline{\theta},\underline{\theta})-\overline{\theta}D_i^*(\overline{\theta};\varnothing,\underline{\theta})$ equals

$$\frac{\left[\overline{\theta}\left(\underline{\theta}E(\theta)-\frac{1-r_j}{1-pr_j}\Delta^2\right)-E(\theta)\left(\underline{\theta}^2-\frac{1-r_j}{1-pr_j}\Delta^2\right)\right](\underline{\theta}-\Delta)W}{(\underline{\theta}-\Delta^2)\left(\underline{\theta}E(\theta)\overline{\theta}-\beta_j\Delta^2\right)}>0,$$

and $\underline{\theta}D_i^*(\underline{\theta};\underline{\theta},\varnothing) - \overline{\theta}D_i^*(\overline{\theta};\varnothing,\varnothing)$ equals

$$\frac{\beta_j\Delta^2\left(E(\theta)\overline{\theta}-\beta_i\underline{\theta}\right)\left(E(\theta)\overline{\theta}-\beta_j\Delta\right)W}{\left(\underline{\theta}E(\theta)\overline{\theta}-\beta_j\Delta^2\right)\left(E(\theta)^2\overline{\theta}^2-\beta_i\beta_j\Delta^2\right)}>0.$$

This completes the proof.

Proof of Proposition 4.8

We show that in equilibrium firms invest more under voluntary disclosure than under mandated disclosure, by showing that marginal research investments under voluntary disclosure exceeds those under mandated disclosure. We focus on symmetric research equilibria, $r_i = R_i = R$ for $i = 1, 2$. We rewrite the marginal research revenues under mandated disclosure as follows:

$$\begin{aligned}\rho R \;=\;& pR\left\{E_{\theta_i}\left(\widehat{\pi}_i(\theta_i,\underline{\theta})\right)-\widehat{\pi}_i(\varnothing,\underline{\theta})\right\}+\\ &+(1-pR)\left\{\frac{(1-p)R}{1-pR}\left[E_{\theta_i}\left(\widehat{\pi}_i(\theta_i,\overline{\theta})\right)-\widehat{\pi}_i(\varnothing,\overline{\theta})\right]+\right.\\ &\left.+\frac{1-R}{1-pR}\left[E_{\theta_i}\left(\widehat{\pi}_i(\theta_i,\varnothing)\right)-\widehat{\pi}_i(\varnothing,\varnothing)\right]\right\}.\end{aligned}$$

The comparison of marginal research revenues given $\Theta_j = \underline{\theta}$ follows directly from lemma 4.3:

$$E_{\theta_i}\left(\pi_i^*(\theta_i;\delta_i^*(\theta_i),\underline{\theta})\right)\geq E_{\theta_i}\left(\widehat{\pi}_i(\theta_i,\underline{\theta})\right),$$

since

$$D_i^*(\underline{\theta};\underline{\theta},\underline{\theta})=\widehat{D}_i(\underline{\theta},\underline{\theta}),\text{ and }D_i^*(\overline{\theta};\varnothing,\underline{\theta})\geq\widehat{D}_i(\overline{\theta},\underline{\theta}),$$

while

$$\pi_i^*(\varnothing;\varnothing,\underline{\theta})\leq\widehat{\pi}_i(\varnothing,\underline{\theta})\text{ since }D_i^*(\varnothing;\varnothing,\underline{\theta})\leq\widehat{D}_i(\varnothing,\underline{\theta}).$$

In the remainder of this proof we show that for $\overline{\theta}$ close to $\underline{\theta}$ and given $\Theta_j \neq \underline{\theta}$, expected marginal research revenues under voluntary disclosure exceed those under mandated disclosure, i.e. $K(R;\overline{\theta}) > 0$, with:

$$\begin{aligned}K(R;\overline{\theta})\;\equiv\;& E_{\theta_i}\left(\pi_i^*(\theta_i;\delta_i^*(\theta_i),\varnothing)\right)-\pi_i^*(\varnothing;\varnothing,\varnothing)+\\ &-\frac{(1-p)R}{1-pR}\left[E_{\theta_i}\left(\widehat{\pi}_i(\theta_i,\overline{\theta})\right)-\widehat{\pi}_i(\varnothing,\overline{\theta})\right]+\\ &-\frac{1-R}{1-pR}\left[E_{\theta_i}\left(\widehat{\pi}_i(\theta_i,\varnothing)\right)-\widehat{\pi}_i(\varnothing,\varnothing)\right].\end{aligned}$$

We make the following steps. First we show that for extreme investment level $R=0$ the inequality holds. Second we show that the difference between marginal research revenues under voluntary and mandated disclosure increases in R, if $\overline{\theta}$ is close to $\underline{\theta}$. From lemma 4.3 (ii.b) we conclude that for $R=0$:

$$
\begin{aligned}
&E_{\theta_i}\left(\pi_i^*(\theta_i;\delta_i^*(\theta_i),\varnothing)\right)-\pi_i^*(\varnothing;\varnothing,\varnothing)= \\
&p\underline{\theta}\widehat{D}_i(\underline{\theta},\varnothing)^2+(1-p)\overline{\theta}\frac{E(\theta)^2}{\overline{\theta}^2}\widehat{D}_i(\varnothing,\varnothing)^2-E(\theta)\widehat{D}_i(\varnothing,\varnothing)^2> \\
&E_{\theta_i}\left(\widehat{\pi}_i(\theta_i,\varnothing)\right)-\widehat{\pi}_i(\varnothing,\varnothing),
\end{aligned}
$$

Given that $K(0)>0$, it suffices to show that for $\overline{\theta}$ sufficiently close to $\underline{\theta}$, $K'(R)>0$ to prove that $K(R)>0$ for all R. It is straightforward to show that:

$$
K'(R;\overline{\theta})=\frac{1-p}{(1-pR)^2}\left(k^*(R;\overline{\theta})-\widehat{k}(\overline{\theta})\right)\frac{1}{2}W^2,
$$

with

$$
k^*(R;\overline{\theta})\equiv 2\Delta\overline{\theta}E(\theta)(\overline{\theta}-E(\theta))\left(\frac{p\underline{\theta}(\underline{\theta}-\Delta)(E(\theta)\overline{\theta}-\beta\Delta)}{(\underline{\theta}E(\theta)\overline{\theta}-\beta\Delta^2)^3}-\frac{\overline{\theta}-(1-p)E(\theta)}{(E(\theta)\overline{\theta}+\beta\Delta)^3}\right),
$$

and

$$
\widehat{k}(\overline{\theta})\equiv\left[E_{\theta_i}\left(\widehat{\pi}_i(\theta_i,\overline{\theta})\right)-\widehat{\pi}_i(\varnothing,\overline{\theta})\right]-\left[E_{\theta_i}\left(\widehat{\pi}_i(\theta_i,\varnothing)\right)-\widehat{\pi}_i(\varnothing,\varnothing)\right].
$$

It is easily verified that $\lim_{\overline{\theta}\downarrow\underline{\theta}}K'(R;\overline{\theta})=0$ for any R. For $K'(R;\overline{\theta})>0$ to hold for some $\overline{\theta}>\underline{\theta}$, it suffices to show that $\lim_{\overline{\theta}\downarrow\underline{\theta}}\left(\frac{\partial K'(R;\overline{\theta})}{\partial\overline{\theta}}\right)>0$. For then there is an $\varepsilon>0$ such that $K'(R)>0$ for $\overline{\theta}\in(\underline{\theta},\underline{\theta}+\varepsilon]$. When we differentiate $K'(R)$ to $\overline{\theta}$ and evaluate it in $\overline{\theta}\downarrow\underline{\theta}$, we obtain the following:

$$
\begin{aligned}
\lim_{\overline{\theta}\downarrow\underline{\theta}}\left(\frac{\partial K'(R;\overline{\theta})}{\partial\overline{\theta}}\right) &= \lim_{\overline{\theta}\downarrow\underline{\theta}}\left(\frac{\partial k^{*\prime}(R;\overline{\theta})}{\partial\overline{\theta}}\right)-\lim_{\overline{\theta}\downarrow\underline{\theta}}\left(\frac{\partial\widehat{k}(\overline{\theta})}{\partial\overline{\theta}}\right) \\
&= \frac{2\Delta p^2[\underline{\theta}-(\underline{\theta}-\Delta)]}{(\underline{\theta}-\Delta)(\underline{\theta}+\Delta)^3}-\frac{2\Delta p\underline{\theta}[-p-(1-p)+1]}{(\underline{\theta}-\Delta)(\underline{\theta}+\Delta)^3} \\
&= \frac{2\Delta^2p^2}{(\underline{\theta}-\Delta)(\underline{\theta}+\Delta)^3}>0.
\end{aligned}
$$

This final result suffices to show that K is positive for all R, which completes the proof.

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Summary in Dutch

Essays over Prikkels in Regulering en Innovatie

Het proefschrift analyseert problemen van prikkels en informatie bij strategisch interactieve bedrijven. In het bijzonder worden problemen in optimale regulering en wedrennen van onderzoek en ontwikkeling (O&O) bestudeerd. We gaan in het onderstaande kort in op de economische aspecten van deze twee problemen.

In de analyse van optimale regulering is asymmetrische informatie tussen de regulator en de industrie over productiekosten belangrijk. Omdat bedrijven superieure informatie en andere belangen hebben dan de regulator, moet de regulator aan bedrijven financiële prikkels geven om hen optimaal te laten produceren. In de industrie worden twee complementaire goederen geproduceerd. Het probleem voor de regulator is om de industrie zodanig in te richten dat de prikkels van bedrijven voor het waarheidsgetrouw rapporteren van de productiekosten en participatie tegen minimale kosten worden verkregen. De regulator kiest tussen een monopolist die twee producten produceert of twee onafhankelijke bedrijven die ieder één product produceren. Naast de organisatie van de industrie, kiest de regulator subsidies en de kans waarmee het eindproduct geproduceerd moet worden.

Bij de keuze tussen monopolistische en onafhankelijke productie weegt de regulator twee effecten tegen elkaar af. Aan de ene kant kan de regulator informatiepacht besparen door kostenrapportages van twee onafhankelijke bedrijven met elkaar te vergelijken en de reguleringsinstrumenten van deze vergelijking af te laten hangen. Als de kosten gecorreleerd zijn, geven de kosten van een bedrijf een indicatie voor de kosten van het andere bedrijf. In dat geval kan op een deel van de subsidie bespaard worden. Hoe sterker de correlatie, des te scherper de indicatie die kosten over elkaar geven en des te meer subsidie bespaard kan worden. Dit effect noemen we het maatstaf-competitie effect. Een monopolist kan zijn kostenrapportages coördineren, waardoor prikkels op basis van kostenvergelijking nutteloos zijn. Aan de andere kant kan de regulator subsidies besparen wegens het feit dat een monopolistische producent zijn kostenreportages op elkaar af kan stemmen. Als onafhankelijke producenten te hoge kosten rapporteren, dan oefenen ze een extern effect op elkaar uit. Als bekend zou zijn dat één bedrijf te hoge kosten rapporteert, zou het andere bedrijf minder prikkels hebben om zijn kosten ook te hoog te rapporteren. Onafhankelijke bedrijven kunnen echter hun kostenreportages niet op elkaar afstemmen, zodat ze door dit externe effect meer subsidie moeten krijgen om de juiste prikkels te geven. Een monopolistische producent internaliseert dit externe effect, hetgeen subsidies bespaart voor de regulator. Dit effect noemen we het internalisatie effect. Zowel de correlatie tussen productiekosten, als de beperkte aansprakelijkheid van bedrijven spelen bij de afweging tussen deze twee effecten een rol. Een gereguleerde industrie met beperkt aansprakelijke bedrijven wordt het best als volgt georganiseerd. Voor lage correlatie kiest de regulator voor monopolistische productie, omdat het internalisatie effect domineert, terwijl voor hoge correlatie onafhankelijke producenten beter zijn voor de welvaart. In hoofdstuk 2 gaan we in meer detail in op deze twee effecten en de optimale reguleringsinstrumenten die deze effecten in zich dragen.

Naast dit reguleringsprobleem onderzoeken we problemen van prikkels in dynamische O&O-wedrennen. Een speciale eigenschap van het probleem is dat bedrijven leren terwijl ze investeren in O&O. De interactie tussen de prikkels van bedrijven om te leren en communiceren over hun uitvinding en prikkels om de uitvinding verder te ontwikkelen worden onder verschillende omstandigheden bestudeerd. Bedrijven leren over hun ontwikkelingskosten en ze leren door in onderzoek te investeren. Dat wil zeggen, onderzoek geeft een bedrijf informatie over zijn ontwikkelingskosten. Nadat bedrijven leren, beslissen ze welke informatie ze willen rapporteren aan hun concurrent. Twee effecten van rapportage staan centraal in de analyse. Ten eerste heeft een prijsrapportage van een bedrijf een strategisch effect. Het geeft zijn rivaal informatie over de relatieve ontwikkelingskostenefficiëntie van het bedrijf. Als verwacht wordt dat een bedrijf een efficiënte investeerder in ontwikkeling is, dan schrikt dit de ontwikkelingsinvesteringen van zijn rivaal af. Dit effect zou bedrijven daarom een prikkel geven om hun kostenreportage zo te kiezen dat ze alleen goed nieuws over zichzelf rapporteren. Het tweede effect is een informatief effect en is tegenovergesteld aan het strategische effect. Als ontwikkelingskosten positief gecorreleerd zijn, dan geeft de kostenrapportage van een bedrijf niet alleen informatie over zijn eigen ontwikkelingskosten, maar geeft ook zijn rivaal informatie over zijn ontwikkelingskosten. Dit geeft bedrijven een prikkel om alleen slecht nieuws aan hun rivaal te rapporteren. Slecht nieuws schrikt de rivaal wegens dit effect af. De interactie tussen deze twee tegenovergestelde effecten bepaalt de prikkels die bedrijven hebben om informatie te verzamelen, te rapporteren en verder te ontwikkelen op basis van hun informatie.

In hoofdstuk 3 beschouwen we een O&O wedren waarin bedrijven altijd leren over de kosten van ontwikkelingsinvesteringen. Bedrijven leren echter imperfect. Omdat bedrijven altijd leren, is het bekend dat een bedrijf geïnformeerd is. Wat niet bekend is, is welke informatie een bedrijf bezit. De kosten van projecten zijn perfect gecorreleerd en daarom domineert het informatief effect. Wanneer bedrijven opbrengsten van de innovatie delen, dan wordt dit effect tegengewerkt door vrijbuiterseffecten. De relatieve kracht van de twee effecten bepaalt de prikkel van bedrijven om te investeren en om informatie prijs te geven. De verifieerbaarheid van informatie is cruciaal in de bepaling van hoe veel informatie er kan en wordt prijsgegeven tussen bedrijven. Niet-verifieerbare informatie kan nooit geloofwaardig worden overgebracht, terwijl verifieerbare informatie alleen voor extreme opbrengstenverdelingen tot ontrafeling leidt.

In hoofdstuk 4 analyseren we een O&O wedren waarin bedrijven anders leren. Wanneer een bedrijf leert, dan leert hij perfect. Maar of een bedrijf leert is onzeker en hangt van zijn onderzoeksinvesteringen af. Omdat de vergaarde informatie verifieerbaar is, staan bedrijven voor de keuze deze informatie prijs te geven of te beweren niet geïnformeerd te zijn. In dit hoofdstuk bestuderen we de effecten van openbaringsregulering op prikkels van bedrijven om te investeren in onderzoek en ontwikkeling. Bovendien onderzoeken we de invloed van correlatie tussen ontwikkelingskosten op de prikkels van bedrijven om informatie prijs te geven en om te investeren. Als informatie perfect gecorreleerd is, dan domineert het informatieve effect en bedrijven geven alleen slecht nieuws prijs. Slecht nieuws maakt een rivaal pessimistischer over zijn ontwikkelingskosten en ontmoedigt zijn ontwikkelingsinvesteringen. Voor onafhankelijk verdeelde kosten verdwijnt het informatieve effect en het strategische effect heerst. Daarom geven bedrijven hun informatie alleen prijs als ze efficiënte ontwikkelingsinvesteerders zijn. En bedrijven investeren agressief in zowel onderzoek als ontwikkeling.

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Jos Jansen graduated in Econometrics from Erasmus University Rotterdam in 1993. He carried out his Ph.D research at the CentER for Economic Research (Tilburg University), and visited GREMAQ (Université de Toulouse 1), and the Department of Economics at Princeton University. Since September 1998 he is a research fellow at the research unit Competitiveness and Industrial Change, of the Wissenschaftszentrum Berlin (WZB).

The thesis contains three essays on incentives in regulation and innovation. The first essay analyzes a problem of optimal regulatory design. Key feature of the problem is that there exists asymmetric information between the regulator and the industry concerning the costs of producing complementary products. The regulatory problem is to organize the industry such that firms' incentives for truthful information revelation and participation are obtained at minimal social cost. The second and third essays analyze problems of dynamic competition in research and development. A special feature is that firms learn about their cost of development while they invest in research. The interaction between the firms' incentives to acquire and communicate information, and their incentives to develop the innovation, is studied. The second essay focuses on the incentive effects of revenue sharing, and the verifiability of acquired information. The focus of the third essay is on effects of disclosure regulation, and correlation of development costs on the firms' incentives to invest and disclose information.

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